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ENGINEERING PROPERTY DETERMINATION
ON ROCKET PROPELLANTS

Final Report

By

M. T. Constantine

Advanced Programs, Rocketdyne
A Division of North American Rockwell Corporation
6633 Canoga Avenue, Canoga Park, California

TECHNICAL REPORT AFRPL-TR-70-147

November, 1970

Group 4
Downgraded At 3-Year Intervals
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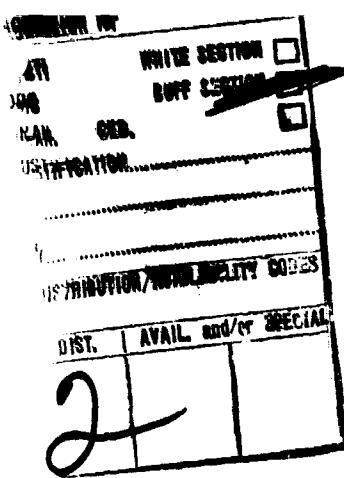
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ENGINEERING PROPERTY DETERMINATION
ON ROCKET PROPELLANTS (u)

⑨ Final Report 6 May 68 - 4-1913

By

⑩ M. T. Constantine

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Advanced Programs, Rocketdyne
A Division of North American Rockwell Corporation
6633 Canoga Avenue, Canoga Park, California

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Any other application which contains any significant part of the subject matter of the above identified application falls within the scope of this order. If such other application does not stand under a secrecy order, it and the common subject matter should be brought to the attention of the Patent Security Division, Patent Office.

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FOREWORD

Sa. AD 503454 (C)

(U) This is the final and summary progress report submitted under G.O. 09079 in compliance with Contract F04611-68-C-0087, Part I, Sub-Item 1AB and Line Item B004 of DD Form 1423. The research reported herein, which covers the period of 6 May 1968 through 4 September 1970, was sponsored by the Air Force Rocket Propulsion Laboratory, Research and Technology Division, Air Force Systems Command, Edwards, California, with Messrs. R. Biggers and F. Forbes acting as the Air Force Project Engineers.

(U) This program was conducted by the Propellant Technology function of the Rocketdyne Research Division, with Dr. K. H. Mueller and Dr. E. A. Lawton serving as Program Managers and Mr. M. T. Constantine serving as the Responsible Project Scientist.

(U) This report has been assigned the Rocketdyne identification number R-8383.

(U) The following technical personnel have contributed to the work described in this report:

Phase I: Literature Survey

K. J. Youel

Phase II: Experimental Determinations

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Dr. J. F. Hon (Specific Heat, Thermal Conductivity)

J. V. Leece (P-V-T Properties, Viscosity)

R. W. Melvold (Specific Heat, P-V-T Properties, Thermal Conductivity)

P. R. Newton (Viscosity)

M. Olsasky (Thermal Conductivity)

W. Polek, Jr. (P-V-T Properties, Sonic Velocity, Surface Tension)

J. Quaglino (P-V-T Properties, Sonic Velocity, Surface Tension, Viscosity, Propellant Storability)

Dr. J. Sinor (Thermal Conductivity, Viscosity)

Dr. R. L. Steele (Thermal Conductivity)

Phase III: Evaluation and Compilation of Data

J. Q. Weber

K. J. Youel

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This technical report has been reviewed and is approved.

Forrest S. Forbes
Chief, Propellant Evaluation Section

ABSTRACT

(U) The results of a 28-month program on the analytical and experimental characterization of the physical properties of selected liquid propellants are presented in three phases. In Phase I, a continual review of the literature was conducted to ensure the acquisition and documentation of current propellant properties data. Phase II experimental efforts have resulted in measurements of: (1) MON-25, Florox, and MHF-7 melting points; (2) IMDFNA, Florox, MOR-5, and MHF-7 densities; (3) IMDFNA vapor and equilibrium pressures, and Florox, MOR-5, and MHF-7 vapor pressures (with calculations of normal boiling points and heats of vaporization of these propellants); (4) N_2O_4 and MON-25 surface tensions; (5) MON-25, Florox, MOR-5, and MHF-7 specific heats; (6) Florox, MOR-5, and MHF-7 viscosities; (7) ClF_5 , ClF_3 , Florox, MOR-5, and MHF-7 thermal conductivities; (8) MON-25, Florox, N_2H_4 , MMH, UDMH, 50 N_2H_4 - 50 UDMH, MHF-3, MHF-5, and MHF-7 sonic velocities (and calculations of their adiabatic compressibilities); and (9) $N_2H_4-N_2H_5N_3$ and Florox thermal stabilities. In addition, long-term storability tests were initiated on Florox, ClF_5 , ClF_3 , MHF-3, and MHF-5 in selected metals. Phase III efforts resulted in the preparation of physical property data sheets on MMH, C_2N_2 , MON, the fuming nitric acids, Florox, MOR-5, and MHF-7; and the assembly of a bibliography on ClF_5 / and ClF_3 /materials interactions.

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 vapor pressure, liquid, 39, G-3, G-7, G-8, G-17, G-18
 viscosity, liquid, 85, G-4, G-9, G-21, G-22
(U) with hydrazine azide (77 w/o N_2H_4 - 23 w/o $N_2H_5N_3$)
 thermal stability, 135
(U) with UDMH (50 w/o N_2H_4 - 50 w/o UDMH)
 compressibility, adiabatic, 43
 dielectric constant, 13
 electrical loss tangent, 13
 sonic velocity (velocity of sound in), 122

(U) Hydrazine, monomethyl- ($CH_3N_2H_3$)
 boiling point, A-2
 compressibility, adiabatic, 44, A-2, A-11, A-12
 compressibility, isothermal, A-2
 critical density, A-2
 critical pressure, A-2
 critical temperature, A-2
 density, liquid, A-2, A-9, A-10
 dielectric constant, liquid, A-4
 dipole moment, A-4
 electrical conductivity, A-4
 enthalpy, A-5, A-21
 entropy, A-5, A-21
 freezing point, A-2
 heat capacity, gas, A-6
 heat capacity, liquid, A-3, A-5, A-19, A-20
 heat capacity, solid, A-3, A-5, A-17, A-18
 heat of combustion, A-3
 heat of formation, A-3
 heat of fusion, A-3
 heat of vaporization, A-3
 molecular weight, A-2
 normal boiling point, A-2
 sonic velocity (velocity of sound), 118, A-4, A-26, A-27
 surface tension, A-3, A-15, A-16
 thermal conductivity, liquid, A-4, A-24, A-25
 thermal expansion, coefficient of, A-2
 vapor pressure, liquid, A-2, A-13, A-14
 viscosity, liquid, A-3, A-22, A-23

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- (C) Hydrazine, monomethyl- mixtures, see Hydrazine mixtures, MHF-3, MHF-5, and MHF-7
- (C) Hydrazine nitrate, see Hydrazine mixtures, MHF-5
- (U) Hydrazine, unsymmetrical dimethyl- $[(\text{CH}_3)_2\text{N}_2\text{H}_2]$ compressibility, adiabatic, 46 sonic velocity (velocity of sound in), 122
- (U) IMDFNA, see fuming nitric acids, IMDFNA
- (U) MDFNA, see fuming nitric acids, MDFNA
- (U) MHF-3, see Hydrazine mixtures, MHF-3
- (U) MHF-5, see Hydrazine mixtures, MHF-5
- (U) MHF-7, see Hydrazine mixtures, MHF-7
- (U) Mixed Oxides of Nitrogen (MON), see Nitrogen tetroxide mixtures, MON-10, MON-25, and MON-30
- (U) MMH, see Hydrazine, monomethyl-
- (U) MON-10, see Nitrogen tetroxide mixtures, MON-10
- (U) MON-25, see Nitrogen tetroxide mixtures, MON-25
- (U) MON-30, see Nitrogen tetroxide mixtures, MON-30
- (U) Nitrogen tetroxide (N_2O_4)
 - dielectric constant, 13
 - electrical loss tangent, 13
 - surface tension, 55
- (U) Nitrogen tetroxide mixtures
- (U) MON-10 (90 w/o N_2O_4 - 10 w/o NO)
 - boiling point, C-2
 - density, liquid, C-2, C-7, C-8
 - freezing point, C-2, C-5, C-6
 - heat of formation, C-2
 - molecular weight, C-2
 - normal boiling point, C-2
 - vapor pressure, liquid, C-2, C-11, C-12
 - viscosity, liquid, C-2, C-17, C-18

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(U) Nitrogen tetroxide mixtures (Cont.)
(U) MON-25 (75 w/o N_2O_4 - 25 w/o NO)
boiling point, C-2
compressibility, adiabatic, 43, C-2, C-9, C-10
density, liquid, C-2, C-7, C-8
freezing point, 18, C-2, C-5, C-6
heat capacity, liquid, 71, C-2, C-15, C-16
heat of formation, C-2
melting point, see freezing point
molecular weight, C-2
normal boiling point, C-2
sonic velocity (velocity of sound), 115, C-2, C-19, C-20
surface tension, 57, C-2, C-13, C-14
vapor pressure, liquid, C-2, C-11, C-12
viscosity, liquid, C-2, C-17, C-18

(U) MON-30 (70 w/o N_2O_4 - 30 w/o NO)
boiling point, C-2
density, liquid, C-2, C-7, C-8
freezing point, C-2, C-5, C-6
heat of formation, C-2
molecular weight, C-2
normal boiling point, C-2
vapor pressure, liquid, C-2, C-11, C-12
viscosity, liquid, C-2, C-17, C-18

with nitric acid, see Fuming Nitric Acids, IMDFNA, MDFNA, RFNA, & WFNA

(U) Propane (C_3H_8)
density, liquid, 13
heat capacity, liquid and gas, 13
heat of vaporization, 13
thermal conductivity, gas, 13
vapor pressure, 13
viscosity, gas, 13

(U) RFNA, see Fuming Nitric Acids, RFNA

(U) UDMH, see Hydrazine, unsymmetrical dimethyl-

(U) UDMH mixtures, see Hydrazine mixtures, with UDMH

(U) WFNA, see Fuming Nitric Acids, WFNA

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INTRODUCTION

(U) In April 1965 under Contract AF04(611)-10546, Rocketdyne initiated analytical and experimental efforts designed as the initial step of an Air Force program to eliminate liquid propellant property data gaps. The requirements for such a program were clearly indicated by the history of propellant development where the acquisition of essential propellant properties data has frequently lagged, delaying development of propulsion systems utilizing the propellants. Thus, out of necessity, many propulsion system development programs have utilized estimated or extrapolated propellant properties data (which have later proved to be misleading and inadequate), or have included propellant characterization studies as a part of the development program (which have proved to be costly and inefficient because of the time limitation).

(U) The initial program to anticipate and alleviate these potential problem areas in Air Force propulsion systems development was a 12-month effort, directed at a rational and systematic physical characterization of selected liquid rocket propellants over applicable temperature and pressure ranges. To meet this overall objective, the program was conducted in three interrelated phases (Ref. 1). Phase I consisted of a literature survey to review and document available liquid propellant properties data. Experimental efforts under Phase II resulted in the measurement of: (1) the thermal conductivity of 50 N₂H₄-50 (CH₃)₂N₂H₂ and CH₃N₂H₃; (2) IRFNA and ClF₅ sonic velocity (and calculation of compressibility); (3) ClF₃ and CH₃N₂H₃ specific heat, and correction of ClF₅ specific heat data; (4) ClF₃ phase properties; and (5) the design and assembly of apparatuses for measurement of inert gas solubility in liquids and liquid viscosities at extended temperatures and pressures. Phase III analytical efforts included the assembly and evaluation of physical property data on MHF-1, MHF-3, ClF₃, and ClF₅ for future correlation and summary publication.

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(C) These analytical and experimental efforts were continued to meet additional liquid propellant property requirements under Contract AF04(611)-11407. In the 24-month, 3-phase follow-on program (Ref. 2) under this contract, the review of the literature was extended to ensure the acquisition and documentation of all liquid propellant properties data. Expansion of the experimental efforts resulted in the measurement of: (1) P-V-T properties (in the critical region) of ClF₃ and ClF₃O, and saturated liquid densities of ClF₃, INT0, and CH₃N₂H₃; (2) sonic velocities in ClF₅, ClF₃, N₂O₄, and MHF-3; (3) surface tensions of MHF-3 and MHF-5; (4) nitrogen and helium gas solubilities in ClF₅ and ClF₃; (5) specific heats of (CH₃)₂N₂H₂, 50 w/o N₂H₄-50 w/o (CH₃)₂N₂H₂, ClF₃, MHF-3, and MHF-5; (6) thermal conductivities of (CH₃)₂N₂H₂, MHF-3, MHF-5, and ClF₅; and (7) viscosities of ClF₅ and ClF₃. In addition, evaluation and assembly of selected data from the literature survey and the experimental efforts provided complete physical property bibliographies on B₂H₆ and N₂H₄, and assembly of N₂H₄ and N₂O₄ physical property data sheets.

(U) The total progress achieved during the related efforts under these two previous programs has resulted in the empirical establishment of much of the essential data required to fill gaps in the physical properties of many present-day and near-term rocket propellants. However, with the continual advancement of the technology and the utilization of new propellants and application concepts, many requirements for additional propellant physical and engineering properties data have been established. As a result of these new requirements, a 3-phase analytical and experimental extension of the previous systematic propellant property characterization efforts under Contracts AF04(611)-10546 and AF04(611)-11407 was continued under Contract F04611-68-C-0087. The period of performance under this contract was originally scheduled for 24 months, but it was extended by two additional increments (to meet new propellant data requirements) to a total span of 28 months. Phase I effort in this program represented a continual review of the literature to document reported propellant properties and to locate data gaps. Phase II effort was directed

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at the continued experimental determination of unavailable and/or questionable engineering data for selected oxidizers and fuels in an order related to current Air Force requirements. Phase III included the compilation, correlation, and evaluation of the data obtained from Phases I and II and the presentation of the valid data in annual technical reports and data sheets for incorporation in the CPIA propellant handbook.

- (U) Although the efforts during the first 12 months of this recent program have been reported previously in an Annual Summary Report (Ref. 3), this report describes each phase of this program in terms of the objective and summarizes the results and accomplishments achieved during the entire 28-month period of performance.

SUMMARY

- (U) Analytical and experimental research conducted during a 28-month program on the rational and systematic engineering characterization of selected liquid rocket propellants is described in three phases. This program extended and expanded the objectives of programs conducted under Contracts AF04(611)-10546 and AF04(611)-11407.
- (U) Phase I consisted of a continual review of current propellant-related literature and efforts of other investigators in the field to ensure the acquisition and documentation of the latest possible propellant properties data for evaluation and possible inclusion into a propellant properties handbook. During this program, a preliminary screening of 10,608 reports resulted in the detailed review of 627 reports for potentially pertinent data.
- (U) The experimental characterization of essential engineering properties of selected propellants was conducted under Phase II. Experimental efforts were directed at determinations of melting point, density, vapor pressure, equilibrium pressure, specific heat, viscosity, thermal conductivity, sonic velocity, surface tension, thermal stability, and propellant storability and compatibility of selected propellants in an order related to their importance to the Air Force.
- (U) Melting point measurements were conducted on MHF-7 using a standard apparatus which had been used previously to determine melting points of MHF-3 and MHF-5. In addition, a calorimeter system used in the specific heat measurements was used to determine the melting point of MON-25 and the triple point temperature of Florox.

- (U) The normal boiling points of IMDFNA, Florox, MOR-5, and MHF-7 were calculated from their vapor pressure correlations.
- (U) Experimental density measurements were conducted with an all-metal variable-volume densimeter and/or a pyrex capillary pycnometer to expand the available density data on Florox and to determine the densities of the nominal IMDFNA and MOR-5 oxidizer formulations and the MHF-7 composition spectrum. The density of a nominal formulation of IMDFNA was determined over a temperature range of -8.5 to 99.8 C (16.7 to 211.6 F). Density measurements on saturated liquid Florox over a temperature range of 54.0 to 164.7 C (129.2 to 328.5 F) extended the high-temperature extremity of previously available data. MOR-5 density measurements were conducted over a temperature range of 12.2 to 97.8 C (54.0 to 208.0 F). MHF-7 density was determined as a function of temperature and composition as a result of measurements on six selected MHF-7 formulations and previous data on the MHF-3 formulation.
- (U) Vapor pressure measurements were conducted on IMDFNA, Florox, MOR-5, and MHF-7. The vapor pressure of a nominal IMDFNA formulation was determined over a temperature range of 15.9 to 250.7 F (-8.9 to 121.5 C), while equilibrium pressure measurements were conducted at 120 F at ullages of 99, 50, 20, and 2 v/o. Additional Florox vapor pressure measurements were conducted over a temperature range of 24.3 to 181.6 C (75.7 to 358.9 F) to increase the accuracy of previously available vapor pressure data. MOR-5 vapor pressure measurements were conducted over the temperature range of -31.4 to 165.0 C (-24.5 to 329.0 F). MHF-7 vapor pressure was measured as a function of composition over the temperature range of -7.8 to 115.5 C (18.0 to 239.9 F).

- (U) Using experimental sonic velocity data resulting from this program and liquid density data, the adiabatic compressibilities of MON-25, Florox, N_2I_4 , MMH, UDMH, 50 N_2H_4 -50 UDMH, MHF-3, MHF-5, and MHF-7 were calculated from thermodynamic relationships.
- (U) Surface tension measurements were conducted on N_2O_4 and MON-25 over temperature ranges of -9.3 to 90.7 C (15.3 to 195.2 F) and -35.3 to 82.2 C (-31.5 to 180.0 F), respectively. The measurements were made through the use of a modified differential capillary rise technique, which involves determinations of the difference in rise of a liquid in two capillaries of different diameters. An experimental apparatus, previously used in surface tension measurements on MHF-3 and MHF-5, was used in measurements below 20 C (68 F), while a heavier-walled apparatus was used at the higher temperatures.
- (U) The latent heats of vaporization of IMDFNA, Florox, MOR-5, and MHF-7 were calculated from the slopes of their vapor pressure equations at their normal boiling points.
- (U) Experimental determinations of liquid propellant specific heats were conducted in an adiabatic calorimeter previously developed and utilized under Contracts AF04(611)-9563, AF04(611)-10546, and AF04(611)-11407. During this program, specific heat measurements were made on MON-25, Florox, MOR-5, and MHF-7.
- (U) Viscosity measurements were conducted on Florox, MOR-5, and MHF-7. An all-metal capillary viscometer, developed during previous programs

under Contracts AF04(611)-10546 and AF04(611)-11407, was used for the measurements on Florox and MOR-5, while pyrex Cannon-Ubbelohde and Zhukov viscometers were used for the MHF-7 measurements.

- (U) In an attempt to expand preliminary data obtained previously under Contract AF04(611)-11407, thermal conductivity measurements were conducted on ClF₅ in a steady-state, concentric-cylinder conductivity cell. Experimental difficulties in use of the steady-state cell with highly reactive oxidizers prompted a Rocketdyne-funded development of a transient ("hot-wire") technique, which was subsequently used under this program to determine the thermal conductivities of ClF₅, ClF₃, Florox, MOR-5, and MHF-7.
- (U) Sonic velocity measurements were conducted in MON-25, Florox, N₂H₄, MMH, UDMH, 50 N₂H₄-50 UDMH, MHF-3, MHF-5, and MHF-7 under saturated liquid conditions over selected temperature ranges using two different interferometers.
- (U) Preliminary thermal stability measurements were conducted on the 77 w/o N₂H₄ - 23 w/o N₂H₅N₃ monopropellant formulation using an experimental technique previously employed by Rocketdyne in similar determinations on hydrazine. In addition to these planned studies, a limited evaluation of the thermal stability of Florox was made during vapor pressure measurements.
- (U) Long-term, ambient-temperature storability tests on ClF₃, ClF₅, Florox, MHF-5, and MHF-7 were initiated in potentially applicable metals of construction including, aluminum 1100, aluminum 2219, stainless steel 321,

Inconel 718, Hastelloy C, maraging steel 250, and titanium 6Al-4V. Each of the storage containers used in these tests was fabricated entirely from the selected material, a design which eliminates bimetallic junctions and non-metallic sealants. Pressure transducers, fabricated from the same materials, are being used to monitor progress of the tests by measuring pressure rises caused by propellant reactions and/or decomposition.

- (U) All propellants used during the physical and engineering property measurements were of propellant-grade quality obtained from commercial manufacturers or were formulated to specified compositions using standard procedures. The techniques applied in the chemical analyses of the propellant samples used in the measurements followed military specification procedures, were equivalent to the specified procedures, or were standard Rocketdyne procedures, which have been developed in the absence of specified procedures.
- (U) Phase III efforts involved the assembly of all data generated by Phases I and II, unification of the data sources, critical comparison of conflicting data, and tabulation and correlation of the results. These efforts resulted in assembly of physical property data sheets for mono-methylhydrazine (MMH), cyanogen (C_2N_2), the mixed oxides of nitrogen (MON), the fuming nitric acids (WFNA, RFNA, and MDFNA), Florox, MOR-5, and MHF-7, which are presented in Appendices A through G, respectively. In addition, a bibliography on ClF_5 / and ClF_3 /materials interactions was assembled as Appendix H.

PHASE I: LITERATURE SEARCH

OBJECTIVE

(U) The Phase I objective represented a continual review of the current propellant-related literature and efforts of other investigators in the field to ensure the acquisition of all reported liquid propellant properties data for evaluation and possible inclusion in a handbook and/or annual technical report. This survey was designed to include, but not necessarily be limited to, the properties of the following fuels and oxidizers:

<u>Oxidizers</u>	<u>Fuels</u>
Liquid Oxygen (LO_2)	Liquid Hydrogen (LH_2)
Chlorine Pentafluoride (ClF_5)	50 N_2H_4 -50 UDMH
Chlorine Trifluoride (ClF_3)	Hydrazine (N_2H_4)
Fluorine (F_2)	MMH ($\text{CH}_3\text{N}_2\text{H}_3$)
Hydrogen Peroxide (H_2O_2)	UDMH $\left[(\text{CH}_3)_2\text{N}_2\text{H}_2 \right]$
Nitrogen Tetroxide (N_2O_4)	Mixed Hydrazine Fuels (MHF)
Mixed Oxides of Nitrogen ($\text{N}_2\text{O}_4\text{-NO}$)	Pentaborane (B_5H_9)
Fuming Nitric Acids	Diborane (B_2H_6)
Liquid Fluorine-Liquid Oxygen Mixtures (FLOX)	Cyanogen (C_2N_2)
Oxygen Difluoride (OF_2)	
Tetrafluorohydrazine (N_2F_4)	
Florox and Florox Mixtures	
Bromine Pentafluoride (BrF_5)	

RESULTS AND ACCOMPLISHMENTS

- (U) A formal survey of current propellant literature, initiated under Contract AF04(611) 10546 (Ref. 1) and continued under Contract AF04(611)-11407 (Ref. 2), was continued as Phase I of this program. The survey included the acquisition, review, and documentation of all available physical and engineering properties data on liquid propellants of interest to the Air Force.
- (U) The total literature survey was accomplished through the use of three different techniques. One part of the effort included a survey of all reports received by Rocketdyne through normal distribution channels. Each of these reports was surveyed with respect to subject matter, and reports containing potential liquid propellant information were selected for detailed review. All pertinent data contained in these reports were documented for future assembly under Phase III.
- (U) This report survey was supplemented by a continual survey of current releases of Chemical Abstracts, NASA CSTAR Abstracts, CPIA Chemical Propulsion Abstracts, DDC Technical Abstract Bulletin, the NBS Cryogenic Data Center's Current Awareness Service, and propellant manufacturers' bulletins. Any pertinent information located through these sources that had not been acquired previously by Rocketdyne was obtained and reviewed in detail.
- (U) To ensure a complete awareness of all available data (and data sources) related to rocket propellants, the third technique involved selective use of the federally sponsored information analysis centers whose services are available to the rocket propulsion industry. The many resources available through these centers were employed when a summary of sources of specific information and data was required on a particular propellant.

(U) During the performance of this program, more than 10,608 reports were surveyed; of this total more than 627 reports were reviewed in detail for pertinent propellant information.

(U) As part of Phase I, comprehensive searches of the chemical and propulsion literature were conducted to locate all available physical properties data for monomethylhydrazine ($\text{CH}_3\text{N}_2\text{H}_3$, MMH), cyanogen (C_2N_2), the mixed oxides of nitrogen, and the fuming nitric acids. Sources checked included the chemical and propulsion abstract sources listed above, Beilstein's Handbuch der Organischen Chemie, and the International Critical Tables. The pertinent data obtained from these searches were used for the Phase III data evaluation on these propellants.

(U) In addition, at the request of the Air Force Project Engineer, three special literature surveys were conducted to locate specific data and information required by AFRPL. An extensive survey for all available data on the dielectric constant and electrical loss tangent for N_2O_4 and the 50 N_2H_4 -50(CH_3) $_2\text{N}_2\text{H}_2$ fuel blend in the temperature range of 32 to 140 F and a frequency range of 1 to 10 GHz indicated none of the required data exist for either propellant (although some dielectric constant data are available on N_2O_4 outside of the desired frequency range). Summary references to sources of available data on propane vapor pressure, heat of vaporization, density (liquid), viscosity (gas), thermal conductivity (gas), and heat capacity (liquid and gas) were located in Ref. 4 and 5 and transmitted to the Air Force Project Engineer by telecon. A complete literature survey was conducted for all data on ClF_5 and ClF_3 materials interactions; the material from this survey, which included the acquisition of NASA and DDC title and abstract bibliographies on the subject, was evaluated and compiled into a bibliography as described under Phase III.

PHASE II: EXPERIMENTAL DETERMINATIONS

OBJECTIVE

- (U) The objective of Phase II was the experimental characterization of essential properties of selected liquid propellants. This phase essentially constituted a 28-month continuation of the efforts initiated under Phase II of Contracts AF04(611)-10546 (Ref. 1) and AF04(611)-11407 (Ref. 2). Selection of the propellants and properties that were experimentally characterized was related to the unavailability of required data and relative importance of the data to the Air Force. Initial efforts emphasized the completion of those propellant properties recommended for initial characterization under the previous programs. Additional efforts continued in an order related to the importance of the data to the Air Force (as determined by the Air Force Project Engineer).
- (U) The selected properties were determined over the liquidus temperature range and over a pressure range of 14.7 to 1000 psi, where practical. Changes to the selected list were made at various times during the program through mutual agreement of Rocketdyne and the Air Force Contracting Officer. Standard test methods were used when available. Wherever unique or new test methods were used, their use was approved by the Air Force Contracting Officer.

RESULTS AND ACCOMPLISHMENTS

- (U) During the 28-month program, Phase II efforts were directed at the measurement of melting point, density, vapor pressure (with calculation of normal boiling point and heat of vaporization), surface tension, specific heat, viscosity, thermal conductivity, sonic velocity (and calculation of compressibility), thermal stability, and storability of selected propellants. (Planned measurements of inert gas solubility and electromagnetic properties of selected propellants were not conducted because of the relative low priority assigned during this program.)

(U) The apparatus and techniques used in these measurements were essentially those used previously in similar efforts conducted under Contracts AF04(611)-10546 (Ref. 1) and AF04(611)-11407 (Ref. 2) with one exception; a new apparatus for the measurement of thermal conductivity, developed under in-house funding, was used to improve the quality, economics, and accuracy of these measurements. In addition, standard techniques were used to evaluate thermal stability and storability.

(U) The efforts and results in each of these areas of property characterization are described in the following paragraphs. Included in the discussions are details of the changes in experimental apparatus or methods instituted during the current program.

Melting Point/Triple Point

Temperature Measurements

(U) Melting point measurements were conducted on MHF-7 using a standard apparatus which had been used previously to determine melting points of MHF-3 and MHF-5 under Contract N0w66-0728-i (Ref. 6). In addition, the calorimeter system used in the specific heat measurements was used to determine the melting point of MON-25 and the triple point temperature of Florox.

(U) The standard melting point apparatus consisted of a glass sample cell closed by Teflon needle valves, and fitted with an internal thermowell and a solenoid-activated reciprocating spiral glass stirrer. Isoamyl alcohol was used as a heat transfer medium in the thermowell. The output from a Cu-constantan thermocouple in the thermowell was fed without amplification to a temperature-calibrated recorder which monitored the temperature of the sample. Calibrations were made by determinations of the melting point of water and the temperature of a dry ice/trichloroethylene slush. The sample cell (containing 5 ml of the sample liquid)

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was inserted through a cork into a strip-silvered Dewar containing a rapidly circulating GN_2 bath. Cooling of the cell was accomplished by allowing LN_2 to boil off in the lower portion of the Dewar, while heating was provided by thermal losses. The samples were cooled with stirring until they froze (some degree of supercooling was observed in all samples), and then warmed (with stirring). The temperature at which the last solid melted (by visual observation) was noted as the melting point. At least triplicate measurements were made on each sample. All transfers of the fuel samples into the sample cell were made in a GN_2 -filled drybox using glass syringes with stainless steel needles; thus all of the melting point measurements conducted in this apparatus were made on a sample under GN_2 pressure of ~ 1 atmosphere.

- (U) The calorimeter used to conduct measurements of the melting point of MON-25 and the triple point temperature of Florox is described under the "Specific Heat Measurements" section.

- (U) Melting Point of MHF-7. Melting point measurements were conducted on six $\text{CH}_3\text{N}_2\text{H}_3-\text{N}_2\text{H}_4-\text{H}_2\text{O}$ formulations (see "Propellant Formulation and Chemical Analyses" section), which represented a 5 w/o variation in component composition around the nominal MHF-7 (81 w/o $\text{CH}_3\text{N}_2\text{H}_3$ -14 w/o N_2H_4 -5 w/o H_2O) formulation. The results of these measurements are shown in Table 1.

TABLE 1
MELTING POINTS OF SELECTED MHF-7 FORMULATIONS

MHF-7 Formulation	Composition				Melting Point	
	$\text{CH}_3\text{N}_2\text{H}_3$, w/o	N_2H_4 , w/o	H_2O , w/o	OSI, w/o	$^{\circ}\text{C} \pm 1.0$	$^{\circ}\text{F} \pm 1.8$
-N (nominal)	81.3	14.2	4.2	0.3	-57.0	-70.6
-1	75.9	14.5	9.3	0.3	Did not Freeze	
-2	76.2	19.1	4.4	0.3	-49.4	-56.9
-3	81.2	8.8	9.5	0.5	-64.1	-83.4
-4	86.5	8.9	4.3	0.3	-59.4	-74.9
-5	80.7	18.7	0.3	0.3	-43.8	-46.8

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(U) As noted in these results, the melting point of the nominal experimental formulation of MHF-7 is -57.0 ± 1.0 C (-70.6 ± 1.8 F). As expected, the melting point is increased as the N_2H_4 content is increased, and decreased as the $CH_3N_2H_3$ and/or H_2O contents are increased. In determinations on one of the high-water formulations (MHF-7-1), the sample appeared to glass during the cooling cycle without ever exhibiting signs of crystal formation. Attempts to correlate all previous melting point data on the $CH_3N_2H_3-N_2H_4-H_2O$ system into a system melting point isotherm diagram was in progress at the conclusion of the program.

(U) Melting Point of MON-25. The adiabatic calorimeter was used to verify the melting point of a sample of MON-25 (sample composition: 75.3 w/o N_2O_4 -24.7 w/o N0) during specific heat measurements in the solid/liquid phase region. The technique involved the measurement of the heat capacities of the liquid and solid/liquid phases of the MON-25 sample and determination of the temperature at which a discontinuity occurs. (A different technique involving development of a warming-curve proved unsuccessful since the calorimeter is not equipped for stirring of the sample.) The heat capacity-temperature plot for these measurements exhibited a discontinuity of infinite proportions at approximately -51 C (-59.8 F). This temperature corresponds (from the two-component phase diagram shown in Appendix C, Fig. C-1 and C-1a) to a mixture containing 24 w/o N0.

(C) Triple Point of Florox. In an attempt to extend the measurement capabilities during this program, a study was initiated during the Florox (ClF_3O) specific heat measurements to investigate the feasibility of determining propellant freezing points (or triple points) and latent heats of fusion with the adiabatic calorimeter. Using this apparatus (as described in the "Specific Heat Measurements" section) the ClF_3O

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(c) triple point temperature was determined by means of DTA measurements to be -41.8 C (-43.2 F). This is in good agreement with a previously reported (Ref. 7) value of -41.7 ± 0.2 C. Heat of fusion data obtained on ClF_3O proved inconclusive because of insufficient data (on the heat capacity of the solid) for determining the magnitude of certain required corrections. Further investigation using a previously characterized compound would appear to be warranted to provide a better evaluation of the technique used.

Normal Boiling Points

(U) The normal boiling points [i.e., the temperature at which the vapor pressure of the material is 1 atm (14.696 psia)] of IMDFNA, Florox, MOR-5, and MHF-7 were calculated from their vapor pressure correlations as given in the "Vapor Pressure Measurement" section.

(U) Normal Boiling Point of IMDFNA. The normal boiling point of an Inhibited Maximum Density Fuming Nitric Acid (IMDFNA) formulation (see the "Propellant Formulation and Chemical Analysis" section) with a composition of 54.3 w/o HNO_3 -44.3 w/o NO_2 -0.33 w/o NO -0.27 w/o H_2O -0.8 w/o HF was calculated as 24.4 C (75.9 F).

(C) Normal Boiling Point of Florox. The normal boiling point of Florox (ClF_3O) with a composition of 99.7 w/o ClF_3O -0.1 w/o ClF_3 -0.1 w/o FClO_2 -0.1 w/o HF was calculated as 30.6 C (87.1 F).

(C) Normal Boiling Point of MOR-5. The normal boiling point of a MOR-5 formulation (nominal composition: 78 w/o ClF_3O -22 w/o ClF_5) with a composition of 78.3 w/o ClF_3O -19.8 w/o ClF_5 -1.6 w/o ClF_3 -0.2 w/o FClO_2 -0.1 w/o HF was calculated as 9.4 C (48.9 F).

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(U) Normal Boiling Point of MHF-7. The normal boiling point of MHF-7 was correlated from the vapor pressure equations as a function of composition by the following expressions:

$$NBP(C) = \frac{496.6 + 5.757 H_{(w/o)} + 7.919 W_{(w/o)}}{7.3742 - 1.507 \times 10^{-2} H_{(w/o)} - 2.073 \times 10^{-2} W_{(w/o)}}$$

and

$$NBP(F) = \frac{1129.8 + 9.88 H_{(w/o)} + 13.59 W_{(w/o)}}{7.3742 - 1.507 \times 10^{-2} H_{(w/o)} - 2.073 \times 10^{-2} W_{(w/o)}}$$

where NBP = normal boiling temperature (at 1 atm) in C or F

$H_{(w/o)}$ = N_2H_4 concentration in weight percent

$W_{(w/o)}$ = H_2O concentration in weight percent

From these expressions the normal boiling point of the nominal MHF-7 formulation (81 w/o $CH_3N_2H_3$ -14 w/o N_2H_4 -5 w/o H_2O) is 87.4 C (189.3 F).

Density Measurements

(U) Experimental measurements were performed to expand the available density data on Florox and to determine the densities of the nominal IMDFNA and MOR-5 oxidizer formulations and the MHF-7 composition spectrum. The density of a nominal formulation of IMDFNA was determined over a temperature range of -8.5 to 99.8 C (16.7 to 211.6 F). Density measurements on saturated liquid Florox over a temperature range of 54.0 to 164.7 C (129.2 to 328.5 F) extended the high-temperature extremity of the previously available data (Ref. 8). MOR-5 density measurements were conducted over a temperature range of 12.2 to 97.8 C (54.0 to 208.0 F). MHF-7 density was determined as a function of temperature and composition as a result of measurements on six selected MHF-7 formulations and previous data on the MHF-3 formulation.

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(U) Two different experimental apparatuses, an all-metal variable-volume densimeter and a pyrex capillary pycnometer (closed), were used in the density measurements. A diagram of the variable-volume apparatus, which was constructed from the design of Poole and Nyberg (Ref. 9), is presented in Fig. 1. This densimeter (previously described in Ref. 2) operates on the principle that a sudden rise in pressure (sensed by the pressure transducer) will occur when all vapor in the variable-volume propellant cell is forced to condense by mechanical reduction of the cavity volume containing both liquid and vapor. The volume of the cell (and thus the contained liquid) at this point is indicated by the position of the micrometer attached to the bellows and a prior calibration of the micrometer (defining the micrometer setting-cell volume relationship of the apparatus) with a liquid of known density. The density of the sample at this point is then calculated from the weight of the propellant sample and the indicated volume.

(U) The apparatus is constructed entirely of 321 stainless steel and is capable of withstanding pressures up to 1500 psi. The volume range provided by the stainless steel bellows permits density measurements over a wide range of temperatures without change of the propellant sample size. The densimeter was placed in a constant-temperature bath for temperature selection and regulation to ± 0.1 F. The temperature of the propellant sample was measured by a chromel-alumel thermocouple taped to the densimeter and was recorded during the density measurement after the propellant sample had reached thermal equilibrium with the environmental bath.

(U) The pyrex capillary pycnometers used in the density measurements are basically converted 10- or 25-ml volumetric flasks. The necks of the flasks were replaced with 4-inch sections of 2-mm bore capillary tubing, which were etched with reference lines and sealed with Fischer-Porter needle valves. For measurements below room temperature, the upper portion of the capillary tubing contained an expansion bulb. A

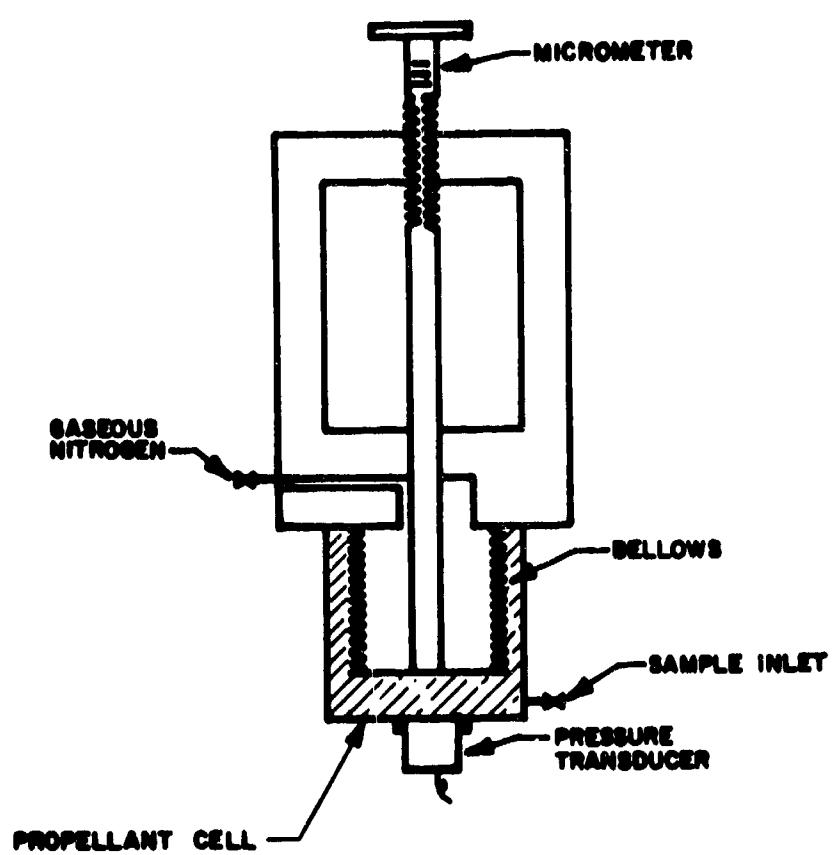


Figure 1. Poole-Nyberg Densimeter

Gaetner cathetometer was used to measure meniscus levels above or below the reference line; these deviations of the meniscus level were recorded to $\pm 5 \times 10^{-4}$ cm. As in the measurements with the densimeter, a constant-temperature bath maintained the desired temperature level of the propellant samples to ± 0.1 F. A Mettler analytical balance was used to determine the apparent sample weights to ± 0.1 mg. Calibrations of the pycnometer volume relative to the reference mark were conducted above 32 F (0 C) using spectrograde chlorobenzene as the calibrating fluid and at temperatures below 32 F using spectrograde acetone.

- (U) A vacuum line was used to load IMDFNA, Florox, and MOR-5 samples into the apparatuses, while samples of the MHF-7 formulations were loaded in a dry box under ~ 1 atmosphere of gaseous nitrogen.
- (U) Density of IMDFNA. Density measurements were conducted on several samples of an Inhibited Maximum Density Fuming Nitric Acid (IMDFNA) formulation (composition: 54.3 w/o HNO_3 -44.3 w/o NO_2 -0.33 w/o NO -0.27 w/o H_2O -0.8 w/o HF) using a combination of the Poole-Nyberg densimeter and a 10-ml pyrex capillary pycnometer. The samples were loaded into both apparatuses under their own vapor pressure through use of a vacuum line. The results of these measurements, presented in Table 2, were correlated over a temperature range of -8.5 to 99.8 C (16.7 to 211.6 F) through use of a least squares curve-fit computer program with the following expressions of density as a function of temperature:

$$\rho \text{ (g/cc)} = 1.6692 - 1.871 \times 10^{-3} t_{(C)} - 6.198 \times 10^{-12} t_{(C)}^5$$

and

$$\rho \text{ (lb/cu.ft)} = 106.28 - 6.473 \times 10^{-2} t_{(F)} - 4.308 \times 10^{-14} t_{(F)}^6$$

The standard errors of estimate for these correlations, which are represented graphically (in metric units) in Fig. 2, are 0.0021 g/cc and 0.13 lb/cu.ft, respectively. Although additional density measurements were made at higher temperatures, indications of propellant decomposition or equilibrium change at temperatures > 220 F resulted in the elimination of these data from the correlation.

TABLE 2

EXPERIMENTAL DENSITY DATA ON SATURATED LIQUID IMDFNA*

Temperature		Observed Density, g/cc	Calculated Density	
C	F		g/cc	lb/cu ft
- 8.5	16.7	1.6843	1.6851	105.20
0.0	32.0	1.6683**	1.6692	104.21
2.9	37.2	1.6659	1.6638	103.87
5.6	42.1	1.6590	1.6588	103.56
6.6	43.9	1.6581**	1.6569	103.44
10.2	50.4	1.6499	1.6501	103.02
15.1	59.2	1.6387	1.6410	102.45
15.55	60.0	1.6388**	1.6401	102.40
21.4	70.5	1.6312	1.6292	101.71
26.6	79.9	1.6211	1.6193	101.10
27.3	81.1	1.6163	1.6181	101.02
29.0	84.2	1.6125	1.6148	100.82
42.0	107.6	1.5911	1.5898	99.25
42.5	108.5	1.5901	1.5888	99.19
50.3	122.5	1.5775	1.5731	98.20
60.2	140.4	1.5473	1.5517	96.87
60.9	141.6	1.5506	1.5501	96.77
70.7	159.3	1.5237	1.5260	95.27
79.5	175.1	1.5016	1.5008	93.70
91.5	196.7	1.4595	1.4583	91.05
99.8	211.6	1.4206	1.4211	88.71

*Sample Composition:

HNO ₃ , w/o	54.3
NO ₂ , w/o	44.3
NO, w/o	0.33
H ₂ O, w/o	0.27
HF, w/o	0.8

**Measurements conducted with
10-ml capillary pycnometer;
all other measurements con-
ducted with Poole-Nyberg
densimeter.

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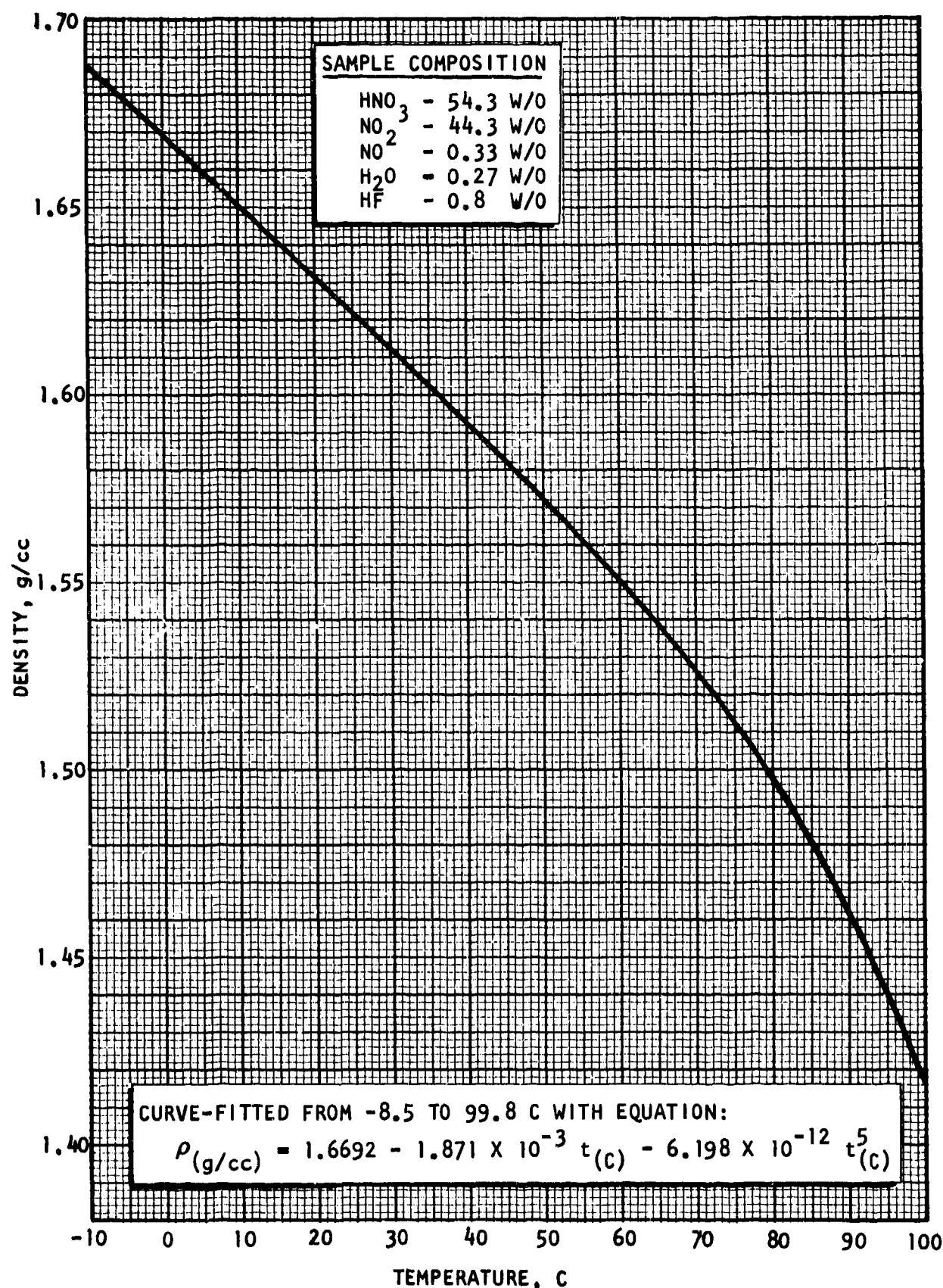


Figure 2. Density of Saturated Liquid IMDFNA

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(c) Density of Florox. With the variable-volume capabilities of the Poole-Nyberg densimeter, it was possible to conduct measurements on propellant-grade Florox (ClF_3O) over the temperature range of 54.0 to 164.7 C (129.2 to 328.5 F) with two fillings of the apparatus. The saturated liquid density data resulting from these measurements are presented in Table 3 along with the chemical analysis of the propellant sample. These density data, together with those obtained from previous experimental measurements (also shown in Table 3), were curve-fit by a least squares computer program over a temperature range of -20.6 to 164.7 C (-5.1 to 328.5 F) with the following equations:

$$\rho_{(\text{g/cc})} = 1.9196 - 2.610 \times 10^{-3}t_{(\text{C})} - 3.427 \times 10^{-6}t_{(\text{C})}^2 - 1.033 \times 10^{-10}t_{(\text{C})}^4$$

and

$$\rho_{(\text{lb/cu ft})} = 122.68 - 8.733 \times 10^{-2}t_{(\text{F})} - 5.370 \times 10^{-5}t_{(\text{F})}^2 - 4.927 \times 10^{-10}t_{(\text{F})}^4$$

The standard errors of estimate for these curve-fits are 0.003 g/cc and 0.2 lb/cu ft, respectively. These expressions are illustrated graphically in Fig. E-1 and E-1a in Appendix E.

(c) Although the data resulting from the measurements form a smooth extension of data obtained previously (Ref. 8), the scatter about each temperature point was greater at temperatures above 120 C (248 F). This is probably caused by the formation of noncondensables formed as a result of the slow thermal decomposition of ClF_3O , which occurs in stainless steel at these temperatures.

(c) Density of MOR-5. Using the Poole-Nyberg densimeter, saturated liquid density measurements were conducted on the MOR-5 (nominal composition: 78 w/o ClF_3O -22 w/o ClF_5) oxidizer blend over the temperature range of 12.2 to 97.8 C (54.0 to 208.0 F) with one filling of the apparatus. The resulting density data are presented in Table 4 along with the chemical composition of the liquid sample. These data were curve-fit by a least squares computer program with the following equations:

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TABLE 3

EXPERIMENTAL DENSITY DATA ON SATURATED LIQUID FLOROX*

Temperature		Observed Density, g/cc	Calculated Density	
C	F		g/cc	lb/cu. ft
-20.6**	-5.1	1.972	1.972	123.12
-12.0**	10.4	1.949	1.950	121.77
-1.1**	30.0	1.925	1.922	120.01
1.8**	35.2	1.914	1.915	119.54
6.3**	43.3	1.906	1.903	118.80
19.5**	67.1	1.865	1.867	116.57
20.0**	68.0	1.863	1.866	116.485
21.1**	70.0	1.862	1.863	116.30
32.4**	90.3	1.830	1.831	114.32
37.0**	98.6	1.820	1.818	113.50
38.1**	100.6	1.814	1.815	113.305
44.3**	111.7	1.795	1.797	112.18
53.1**	127.6	1.772	1.770	110.54
54.0	129.2	1.775	1.768	110.365
55.8**	132.4	1.765	1.762	110.02
56.0**	132.8	1.760	1.762	109.98
68.2**	154.8	1.723	1.723	107.60
68.5**	155.3	1.721	1.722	107.54
74.3**	165.7	1.699	1.704	106.36
75.1**	167.2	1.704	1.701	106.20
80.6	177.2	1.685	1.683	105.05
87.0**	188.6	1.659	1.661	103.68
87.5**	189.5	1.661	1.659	103.57
93.9	201.0	1.633	1.636	102.15
104.9	220.8	1.595	1.596	99.61
116.7	242.1	1.540	1.549	96.705
131.6	268.9	1.491	1.486	92.74
137.2	279.0	1.467	1.460	91.16
145.6	294.1	1.420	1.420	88.67
156.5	313.7	1.363	1.365	85.23
164.7	328.5	1.320	1.321	82.47

*Sample Composition:

C1F ₃ O, w/o	99.7
C1F ₃ , w/o	0.1
FC1O ₂ , w/o	0.1
HF, w/o	0.1

**Data taken from Ref. 8.

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$$(c) \rho_{(g/cc)} = 1.902 - 2.396 \times 10^{-3}t_{(C)} - 9.019 \times 10^{-6}t_{(C)}^2$$

and

$$\rho_{(lb/cu\ ft)} = 121.25 - 7.199 \times 10^{-2}t_{(F)} - 1.738 \times 10^{-4}t_{(F)}^2$$

The standard errors of estimate of these expressions are 0.003 g/cc and 0.21 lb/cu ft, respectively. Graphical representations of these expressions are shown in Fig. F-2 and F-2a in Appendix F.

TABLE 4

EXPERIMENTAL DENSITY DATA ON SATURATED LIQUID MOR-5*

(c)

Temperature		Observed Density, g/cc	Calculated Density	
C	F		g/cc	lb/cu ft
12.2	54.0	1.872	1.871	116.86
17.1	62.8	1.857	1.859	116.04
22.3	72.1	1.848	1.844	115.15
45.3	113.5	1.775	1.775	110.83
64.0	147.2	1.710	1.712	106.44
74.1	165.4	1.674	1.675	104.59
86.6	155.9	1.632	1.627	101.59
97.8	208.0	1.579	1.582	98.75

* Sample Composition:

C₁F₃O, w/o 75.3

C₁F₅, w/o 24.6

HF, w/o 0.1

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(U) Density of MHF-7. Experimental density measurements were conducted on 6 selected MHF-7 formulations (described in the "Propellant Formulation and Chemical Analyses" section as formulations -N, -1, -2, -3, -4, and -5) over the temperature range of -65.1 to 175.0 F (-53.9 to 79.4 C), using 25-ml pyrex capillary pycnometers. The resulting data (shown in Table 5 with the corresponding chemical analyses of the formulations) were correlated as a function of temperature and composition with previously determined (Ref. 6) data on MHF-3 (shown in Table 6) through the use of a least squares curve-fit computer program. The correlation, which represents a ± 5 w/o variation of each of the formulation components from a nominal MHF-7 formulation (81 w/o $\text{CH}_3\text{N}_2\text{H}_3$ -14 w/o N_2H_4 -5 w/o H_2O), is represented by the following expressions:

$$\begin{aligned}\rho_{(\text{g/cc})} = & 0.8956 - 9.779 \times 10^{-4} t_{(\text{C})} - 1.83 \times 10^{-7} t_{(\text{C})}^2 \\ & + 2.652 \times 10^{-3} W_{(\text{w/o})} + 1.202 \times 10^{-3} H_{(\text{w/o})} \\ & + 5.11 \times 10^{-6} W_{(\text{w/o})} t_{(\text{C})} + 1.64 \times 10^{-6} H_{(\text{w/o})} t_{(\text{C})}\end{aligned}$$

and

$$\begin{aligned}\rho_{(\text{lb/cu ft})} = & 57.00 - 3.369 \times 10^{-2} t_{(\text{F})} - 3.53 \times 10^{-6} t_{(\text{F})}^2 \\ & + 0.1599 W_{(\text{w/o})} + 7.325 \times 10^{-2} H_{(\text{w/o})} \\ & + 1.77 \times 10^{-4} W_{(\text{w/o})} t_{(\text{F})} + 5.67 \times 10^{-5} H_{(\text{w/o})} t_{(\text{F})}\end{aligned}$$

where ρ = density in g/cc or lb/cu ft

t = temperature in C or F

$H_{(\text{w/o})}$ = N_2H_4 content in weight percent

$W_{(\text{w/o})}$ = H_2O content in weight percent

The standard errors of estimate of these expressions are 0.00047 g/cc and 0.03 lb/cu ft, respectively. Graphical representations of the nominal MHF-7 formulation as described by these expressions are shown in Fig. G-1 and G-1a of Appendix G.

TABLE 5
EXPERIMENTAL LIQUID DENSITY DATA FOR MHF-7

Formulation	Temperature, F	Density, g/cc
MHF-7-N	-65.1	0.9735
MHF-7-N	- 5.7	0.9429
MHF-7-N	32.0	0.9240
MHF-7-N	77.0	0.9005
MHF-7-N	138.2	0.8683
MHF-7-N	175.0	0.8490
MHF-7-1	-65.1	0.9862
MHF-7-1	- 5.7	0.9565
MHF-7-1	32.0	0.9381
MHF-7-1	77.0	0.9150
MHF-7-1	138.2	0.8832
MHF-7-1	175.0	0.8644
MHF-7-2	-50.1	0.9723
MHF-7-2	- 5.7	0.9496
MHF-7-2	32.0	0.9307
MHF-7-2	77.0	0.9073
MHF-7-2	138.2	0.8748
MHF-7-2	175.0	0.8561
MHF-7-3	-65.1	0.9804
MHF-7-3	- 5.7	0.9503
MHF-7-3	32.0	0.9314
MHF-7-3	77.0	0.9082
MHF-7-3	138.2	0.8766
MHF-7-3	175.0	0.8577
MHF-7-4	-65.1	0.9676
MHF-7-4	- 5.7	0.9371
MHF-7-4	32.0	0.9172
MHF-7-4	77.0	0.8936
MHF-7-4	138.2	0.8615
MHF-7-4	175.0	0.8423

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TABLE 5. (CONCLUDED)

Formulation	Temperature, F	Density, g/cc
MHF-7-5	-44.0	0.9580
MHF-7-5	-5.7	0.9373
MHF-7-5	32.0	0.9188
MHF-7-5	77.0	0.8950
MHF-7-5	138.2	0.8622
MHF-7-5	175.0	0.8430

SAMPLE COMPOSITIONS

Formulation	CH ₃ NH ₂ , w/o	N ₂ H ₄ , w/o	H ₂ O, w/o	Other Soluble Impurities, w/o
MHF-7-N	81.3	14.2	4.2	0.3
MHF-7-1	75.9	14.5	9.3	0.3
MHF-7-2	76.2	19.1	4.4	0.3
MHF-7-3	81.2	8.8	9.5	0.5
MHF-7-4	86.5	8.9	4.3	0.3
MHF-7-5	80.7	18.7	0.3	0.3

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TABLE 6

EXPERIMENTAL LIQUID DENSITY DATA FOR MHF-3 (Ref. 6)

Formulation	Temperature, F	Density, g/cc
MHF-3	200.6	0.8219
MHF-3	186.0	0.8294
MHF-3	158.6	0.8451
MHF-3	122.4	0.8649
MHF-3	86.0	0.8840
MHF-3	32.1	0.9130
MHF-3	- 31.9	0.9471
MHF-3	- 65.2	0.9648
MHF-3A	200.0	0.8202
MHF-3A	158.6	0.8434
MHF-3A	86.0	0.8826
MHF-3A	32.1	0.9111
MHF-3A	- 31.9	0.9449
MHF-3A	- 70.1	0.9641
MHF-3W	200.0	0.8255
MHF-3W	158.6	0.8484
MHF-3W	122.4	0.8683
MHF-3W	86.0	0.8873
MHF-3W	32.1	0.9160
MHF-3W	- 31.9	0.9506
MHF-3W	- 65.2	0.9672
MHF-3AM	200.0	0.8190
MHF-3AM	158.6	0.8423
MHF-3AM	86.0	0.8816
MHF-3AM	32.1	0.9102
MHF-3AM	- 31.9	0.9436
MHF-3AM	- 65.2	0.9612

SAMPLE COMPOSITIONS

Formulation	CH ₃ N ₂ H ₃ , w/o	N ₂ H ₄ , w/o	H ₂ O, w/o	Other Soluble Impurities, w/o
MHF-3	85.6	13.9	0.3	0.2
MHF-3A	87.3	12.2	0.4	0.1
MHF-3W	85.1	12.8	1.7	0.4
MHF-3AM	89.0	9.4	1.2	0.4

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Vapor and Equilibrium Pressure Measurements

(U) Vapor pressure measurements were conducted on IMDFNA, Florox, MOR-5, and MHF-7. The vapor pressure of a nominal IMDFNA formulation was determined over a temperature range of 15.9 to 250.7 F (-8.9 to 121.5 C). Because some other fuming nitric acid mixtures (with lower NO₂ content) exhibit changes in equilibrium with time at various temperature levels, equilibrium pressure measurements were conducted on IMDFNA at 120 F at ullages of 99, 50, 20, and 2 v/o. Additional Florox vapor pressure measurements were conducted over a temperature range of 24.3 to 181.6 C (75.7 to 358.9 F) to increase the accuracy of previously available vapor pressure data (Ref. 2 and 8). MOR-5 vapor pressure measurements were conducted over the temperature range of -31.4 to 165.0 C (-24.5 to 329.0 F). MHF-7 vapor pressure was measured as a function of composition over the temperature range of -17.8 to 115.5 C (18.0 to 239.9 F).

(U) The apparatus used in the vapor pressure measurements consisted of a 10-milliliter, stainless-steel (type 304) cylinder with immersion thermocouple, pressure transducer, and 316 stainless steel Hoke sample valve. The thermocouple, a chromel-alumel junction with stainless steel (type 316) sheath, was sealed into the cylinder with a swedge fitting, thus permitting direct measurement of the temperature of the cylinder contents. The thermocouple was calibrated at the melting and boiling points of water. The 316 stainless steel pressure transducer (either a Taber 0-50 psia or CEC 0-2000 psia model, depending on the pressure range) was calibrated with a Heise gage over the temperature and pressure ranges of intended use.

(U) In the experimental determinations, the vapor pressure apparatus was loaded through use of a vacuum line with various known liquid quantities of the pertinent propellants. As the temperature of each liquid sample was increased or decreased in increments through heating or cooling of the apparatus in a regulated (to ± 1.0 C) temperature bath or Delco

precision oven, the pressure of the sample was recorded at the attainment of equilibrium temperature at several selected levels. This pressure represented the vapor pressure of the particular propellant as long as both liquid and vapor phases were still present.

(U) The equilibrium pressure measurements on IMDFNA were conducted in stainless steel (type 304) Hoke cylinders of 10-ml capacity, which were fitted with stainless steel (type 304) Hoke needle valves and stainless steel (type 316) pressure transducers. The pressure range of the transducers was 0-2000 psia, and was based on the range of equilibrium pressures exhibited by other fuming nitric acids. The containers were loaded by means of a vacuum line with IMDFNA samples to ullages of 99, 50, 20, 2 v/o at the test temperature.

(U) Vapor Pressure of IMDFNA. Vapor pressure measurements were conducted on several samples of Inhibited Maximum Density Fuming Nitric Acid (IMDFNA) over a temperature range of 15.9 to 250.7 F (-8.9 to 121.5 C). A correlation of the resulting data (given in Table 7 with the sample composition) by a least squares curve-fit computer program resulted in the following expressions of pressure as a function of temperature:

$$\log P_{(\text{psia})} = 9.3329 - \frac{6392.8}{t_{(\text{F})} + 707}$$

and

$$\log P_{(\text{atm})} = 8.1664 - \frac{3552.2}{t_{(\text{C})} + 410.6}$$

The standard error of estimate of these correlations is 2.2% in P. A graphical representation of these correlations is given (in English units) in Fig. 3. During measurements >220 F (104.4 C) there was some evidence of slight pressure fluxuations indicative of changes in the sample composition equilibrium.

TABLE 7
VAPOR PRESSURE DATA ON IMDNA*

Temperature		Observed Pressure, psia	Calculated Pressure	
C	F		psia	atm
- 8.9	15.9	3.2	3.1	0.21
- 2.4	27.7	4.2	4.3	0.29
2.7	36.9	5.4	5.5	0.37
8.9	48.0	7.4	7.3	0.50
15.8	60.5	10.1	10.1	0.69
23.0	73.4	14.1	13.8	0.94
32.8	91.0	20.0	21.0	1.43
40.2	104.4	27.9	28.5	1.94
46.5	115.7	36.1	36.5	2.48
46.7	116.0	36.4	36.7	2.50
53.7	128.6	48.2	48.1	3.27
54.2	129.5	48.9	49.0	3.34
65.3	149.5	76.0	74.0	5.03
75.0	167.0	107.0	104.3	7.10
84.5	184.1	149.0	144.2	9.81
93.9	201.0	200.5	196.0	13.34
104.6	220.3	273.0	274.7	18.69
113.5	236.3	353.5	359.6	24.47
121.5	250.7	444.5	454.7	30.94

*Sample Composition:

HN ₃ , w/o	54.3
NO ₂ , w/o	44.3
NO, w/o	0.33
H ₂ O, w/o	0.27
HF, w/o	0.8

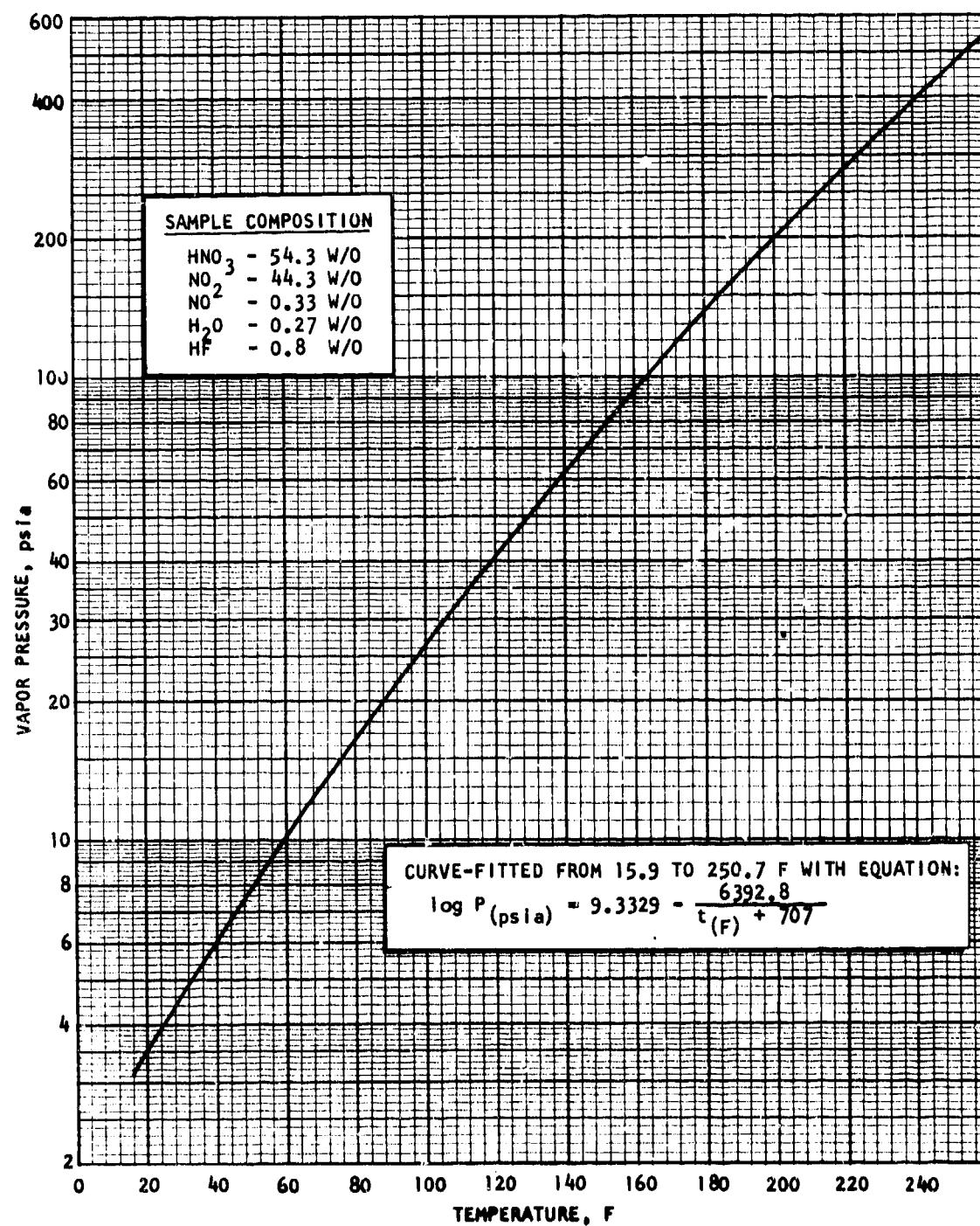


Figure 3. Vapor Pressure of IMDFNA

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(U) Equilibrium Pressure of IMDFNA. Equilibrium pressure measurements were conducted at 120 F (48.9 C) on IMDFNA samples (54.3 w/o HNO₃-44.3 w/o NO₂-0.33 w/o N0-0.27 w/o H₂O-0.8 w/o HF) at ullages of 99, 50, 20, and 2 v/o. During a test period of 84 hours, there was no observable pressure rise in any of the test cells after thermal equilibrium had been achieved (a period of ~1 hr.). With the exception of the cell with 99 v/o ullage, the pressures recorded in each of the cells were equal (within instrument error) to the vapor pressure (40 psia) of the IMDFNA at the test temperature. The high ullage cell with a pressure of 25 psia indicated the quantity of IMDFNA in the test cell was insufficient to achieve a vapor-liquid equilibrium. On the basis of these data and experimental anomalies recorded during density and vapor pressure measurements, it is concluded that acid decomposition and equilibrium changes do not occur until temperatures of >220 F (104 C) are reached. Therefore, planned equilibrium pressure measurements at 40, 60, and 80 F were not conducted.

(C) Vapor Pressure of Florox. Vapor pressure measurements were conducted on Florox (ClF₃O) over a temperature range of 24.3 to 181.6 C (75.7 to 358.9 F) using the constant volume apparatus. The resulting experimental data, presented in Table 8 with the sample composition, were combined with previously reported data (Ref. 2 and 8) and curve-fitted over a temperature range of -23.2 to 181.6 C (-8.7 to 358.9 F) by a least squares computer program. The resulting curve fit gave the following vapor pressure equations:

$$\log P_{(\text{atm})} = 4.7385 - \frac{1317.34}{t_{(\text{C})} + 247.4}$$

and

$$\log P_{(\text{psia})} = 5.9057 - \frac{2371.2}{t_{(\text{F})} + 413.3}$$

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TABLE 8

(c)

VAPOR PRESSURE DATA ON FLOROX*

Temperature		Observed Pressure, psia	Calculated Pressure	
C	F		psia	atm
24.3	75.7	10.0	11.4	0.776
42.3	108.1	22.5	22.8	1.55
87.1	189.8	97.6	92.8	6.31
96.2	205.2	120.0	118.0	8.03
108.6	227.5	167.2	160.4	10.91
132.7	270.9	274.2	275.4	18.74
148.3	298.9	371.6	377.4	25.68
160.2	320.4	465.1	471.8	32.10
168.1	334.6	542.4	543.5	36.98
181.6	358.9	691.8	683.8	46.53

*Sample Composition:

PRE RUN: ClF_3O , w/o 99.7
 ClF_3 , w/o 0.1
 FClO_2 , w/o 0.1
HF, w/o 0.1

The standard deviations for these equations are 3.8 percent. These expressions are represented graphically in Fig. E-3 and E-3a of Appendix E.

(C) The vapor pressure data were obtained from four runs, each of which were terminated at successively higher temperatures from 130 to 181.6 C (266 to 358.9 F). Post-run analyses indicated that increasing amounts of noncon-

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densables (at -80 C) were formed as the temperature of the run increased. These noncondensables, which were identified as molecular oxygen and ClF, result from the slow thermal decomposition of ClF₃O in contact with stainless steel at temperatures greater than 120 C (248 F). Attempts to correlate decomposition rate with increasing temperature are given in the "Thermal Stability Measurements" section.

(C) Vapor Pressure of MOR-5. Vapor pressure measurements were conducted on MOR-5 (nominal composition: 78 w/o Florox - 22 w/o ClF₅) over a temperature range of -31.4 to 165.0 C (-24.5 to 329.0 F) using the vapor pressure apparatus previously described. The resulting data, presented in Table 9 with the sample composition, were curve-fitted by a least squares computer program with the following equations:

$$\log P_{(\text{atm})} = 4.6181 - \frac{1305.0}{T_{(\text{K})}}$$

and

$$\log P_{(\text{psia})} = 5.7853 - \frac{2349.0}{T_{(\text{R})}}$$

The standard error of estimate for these expressions, which are graphically represented in Fig. F-3 and F-3a in Appendix F, is 4% in pressure. It should be noted that the pressures measured above a temperature of ~130 C (266 F) may represent some anomalies resulting from slow decomposition of the ClF₃O which is initiated at this temperature level.

(U) Vapor Pressure of MHF-7. Vapor pressure measurements were conducted on MHF-7 formulations -N, -1, and -2 (see the "Propellant Formulation and Chemical Analyses" section) over the temperature range of -7.8 to 115.5 C (18.0 to 239.9 F). The data, given in Table 10 with the sample compositions, were correlated as a function of temperature and composition by a least squares computer curve-fit program with the following equations:

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TABLE 9
VAPOR PRESSURE DATA ON MOR-5*

Temperature		Observed Pressure, psia,	Calculated Pressure	
C	F		psia	atm
-31.4	-24.5	2.7	2.4	0.16
-23.0	-9.4	3.4	3.7	0.25
-16.4	2.5	4.7	5.0	0.34
0.0	32.0	10.0	10.1	0.69
9.6	49.3	14.9	14.8	1.01
25.4	77.7	27.6	26.0	1.77
31.6	88.9	32.5	31.9	2.17
44.3	111.7	47.8	47.3	3.22
45.6	114.1	50.2	49.2	3.34
58.4	137.1	71.8	70.7	4.81
62.9	145.2	79.3	79.8	5.43
64.2	147.6	81.6	82.6	5.62
70.2	154.4	98.2	96.5	6.57
74.4	165.9	111.9	107.3	7.30
75.5	167.9	108.6	110.3	7.51
81.9	179.4	128.2	128.8	8.76
89.5	193.1	149.6	153.8	10.47
93.6	200.5	165.7	168.7	11.48
98.2	208.8	192.9	186.7	12.70
100.5	212.9	189.2	196.2	13.35
105.2	221.4	210.2	216.9	14.76
114.3	237.7	247.3	261.3	17.78
153.8	308.8	549.0	535.5	36.44
165.0	329.0	658.0	641.1	43.62

* Sample Composition:

ClF ₃ 0, w/o	78.3
ClF ₅ , w/o	19.8
ClF ₃ , w/o	1.6
FC1O ₂ , w/o	0.2
HF, w/o	0.1

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TABLE 10
VAPOR PRESSURE DATA ON MHF-7 FORMULATIONS

Formulation	Temperature		Observed Pressure, psia	Calculated Pressure	
	C	F		psia	atm
MHF-7-N	- 7.8	18.0	0.6*	-	-
MHF-7-N	4.8	40.6	0.8*	-	-
MHF-7-N	21.5	70.7	1.1	1.1	0.07
MHF-7-N	47.0	116.6	3.6	3.3	0.22
MHF-7-N	69.2	156.6	7.3	7.9	0.54
MHF-7-N	85.7	186.3	14.0	14.3	0.97
MHF-7-N	98.0	208.4	21.6	21.7	1.48
MHF-7-N	115.5	239.9	37.4	38.0	2.59
MHF-7-1	50.0	122.0	2.8	2.9	0.20
MHF-7-1	94.2	201.6	15.3	14.9	1.01
MHF-7-2	25.1	77.2	1.0	1.1	0.07
MHF-7-2	51.4	124.5	3.3	3.3	0.22
MHF-7-2	93.1	199.6	16.2	15.4	1.05

SAMPLE COMPOSITIONS

Formulation	CH ₃ NH ₃ , w/o	N ₂ H ₄ , w/o	H ₂ O, w/o	Other Soluble Impurities, w/o
MHF-7-N	81.3	14.2	4.2	0.3
MHF-7-1	79.5	14.5	9.3	0.3
MHF-7-2	76.2	19.1	4.4	0.3

*This point was eliminated from the curve fit.

$$\log P_{(\text{atm})} = 7.3742 - \frac{3313.5}{t(\text{C}) + 382} - 1.507 \times 10^{-2} H_{(\text{w/o})} - 2.073 \times 10^{-2} W_{(\text{w/o})}$$

and

$$\log P_{(\text{psia})} = 8.5414 - \frac{5964.3}{t(\text{F}) + 655.6} - 1.507 \times 10^{-2} H_{(\text{w/o})} - 2.073 \times 10^{-2} W_{(\text{w/o})}$$

where P = vapor pressure in atm or psia
 t = temperature in C or F
 $H_{(\text{w/o})}$ = N_2H_4 concentration in weight percent
 $W_{(\text{w/o})}$ = H_2O concentration in weight percent

The standard errors of estimate for these expressions are 6% in P . The expressions are represented graphically for the nominal MHF-7 composition in Fig. G-3 and G-3a of Appendix G.

(U) Adiabatic Compressibility

(U) Using the experimental sonic velocity data resulting from this program (as discussed in the "Sonic Velocity Measurements" section) and liquid density data, the adiabatic compressibilities of MON-25, Florox, N_2H_4 , MMH, UDMH, 50 N_2H_4 - 50 UDMH, MHF-3, MHF-5, and MHF-7 were calculated from the thermodynamic relationship:

$$\beta_s = \frac{1}{\rho c^2}$$

where

β_s = adiabatic compressibility of the liquid
 ρ = density of the liquid
 c = velocity of sound in the liquid

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(U) Adiabatic Compressibility of MON-25. The adiabatic compressibility of MON-25 (nominal composition: 75 w/o N_2O_4 - 25 w/o NO) was calculated from the experimental sonic velocity data and the density correlation given in Appendix C (Fig. C-2). Least squares curve fit expressions of MON-25 adiabatic compressibility as a function of temperature over a range of -51.4 to 86.9 C (-60.5 to 188.4 F) are:

$$\begin{aligned}\beta_s (\text{atm}^{-1}) = & 5.321 \times 10^{-5} + 4.754 \times 10^{-7} t(C) + 2.950 \times 10^{-9} t(C)^2 \\ & + 2.03 \times 10^{-11} t(C)^3 + 2.55 \times 10^{-13} t(C)^4\end{aligned}$$

and

$$\begin{aligned}\beta_s (\text{psi}^{-1}) = & 3.103 \times 10^{-6} + 1.452 \times 10^{-8} t(F) + 4.94 \times 10^{-11} t(F)^2 \\ & + 2.52 \times 10^{-14} t(F)^3 + 1.65 \times 10^{-15} t(F)^4\end{aligned}$$

The standard errors of estimate for these expressions, which are represented graphically in Fig. C-3 and C-3a in Appendix C, are $1.51 \times 10^{-7} \text{ atm}^{-1}$ and $1.03 \times 10^{-8} \text{ psi}^{-1}$, respectively.

(C) Adiabatic Compressibility of Florox. The experimental Florox (ClF_3O) sonic velocity data were used with experimental ClF_3O saturated liquid density data to calculate the adiabatic compressibility (β_s) of this oxidizer. The equations resulting from curve fits of the calculated data over the temperature range of -31.0 to 61.4 C (-23.8 to 142.6 F) are as follows:

$$\begin{aligned}\beta_s (\text{atm}^{-1}) = & 6.268 \times 10^{-5} + 5.665 \times 10^{-7} t(C) + 3.450 \times 10^{-9} t(C)^2 \\ & + 1.921 \times 10^{-11} t(C)^3 + 2.049 \times 10^{-13} t(C)^4\end{aligned}$$

and

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$$\begin{aligned}\beta_s(\text{psi}^{-1}) = & 3.648 \times 10^{-6} + 1.729 \times 10^{-8}t(F) + 5.909 \times 10^{-11}t(F)^2 \\ & + 5.417 \times 10^{-14}t(F)^3 + 1.328 \times 10^{-15}t(F)^4\end{aligned}$$

The standard errors of estimate for these expressions are 5.06×10^{-8} atm⁻¹ and 3.44×10^{-9} psi⁻¹, respectively. Figures E-2 and E-2a of Appendix E are graphical illustrations of these expressions.

(U) Adiabatic Compressibility of N₂H₄. Experimental sonic velocity data were utilized with existing density data (Ref. 2) to obtain the adiabatic compressibility of hydrazine (N₂H₄). The curve fits resulting from a least squares computer program correlation over a temperature range of 6.1 to 96.5 C (43.0 to 205.7 F) are represented by the following equations:

$$\beta_s(\text{atm}^{-1}) = 2.081 \times 10^{-5} + 1.031 \times 10^{-7}t(C) + 2.73 \times 10^{-10}t(C)^2$$

and

$$\beta_s(\text{psi}^{-1}) = 1.297 \times 10^{-6} + 3.530 \times 10^{-9}t(F) + 5.73 \times 10^{-12}t(F)^2$$

The standard errors of estimate of these equations are 7.33×10^{-10} atm⁻¹ and 4.99×10^{-11} psi⁻¹, respectively. Figure 4 is a graphical representation of the metric system expression.

(U) Adiabatic Compressibility of MMH. The sonic velocity and liquid density (Appendix A) data on monomethylhydrazine, MMH or CH₃N₂H₃, were used to calculate its adiabatic compressibility over a temperature range of -31.9 to 95.6 C (-25.4 to 204.1 F). The following equations (represented graphically in Fig. A-2 and A-2a of Appendix A) are least squares curve fits of these calculations:

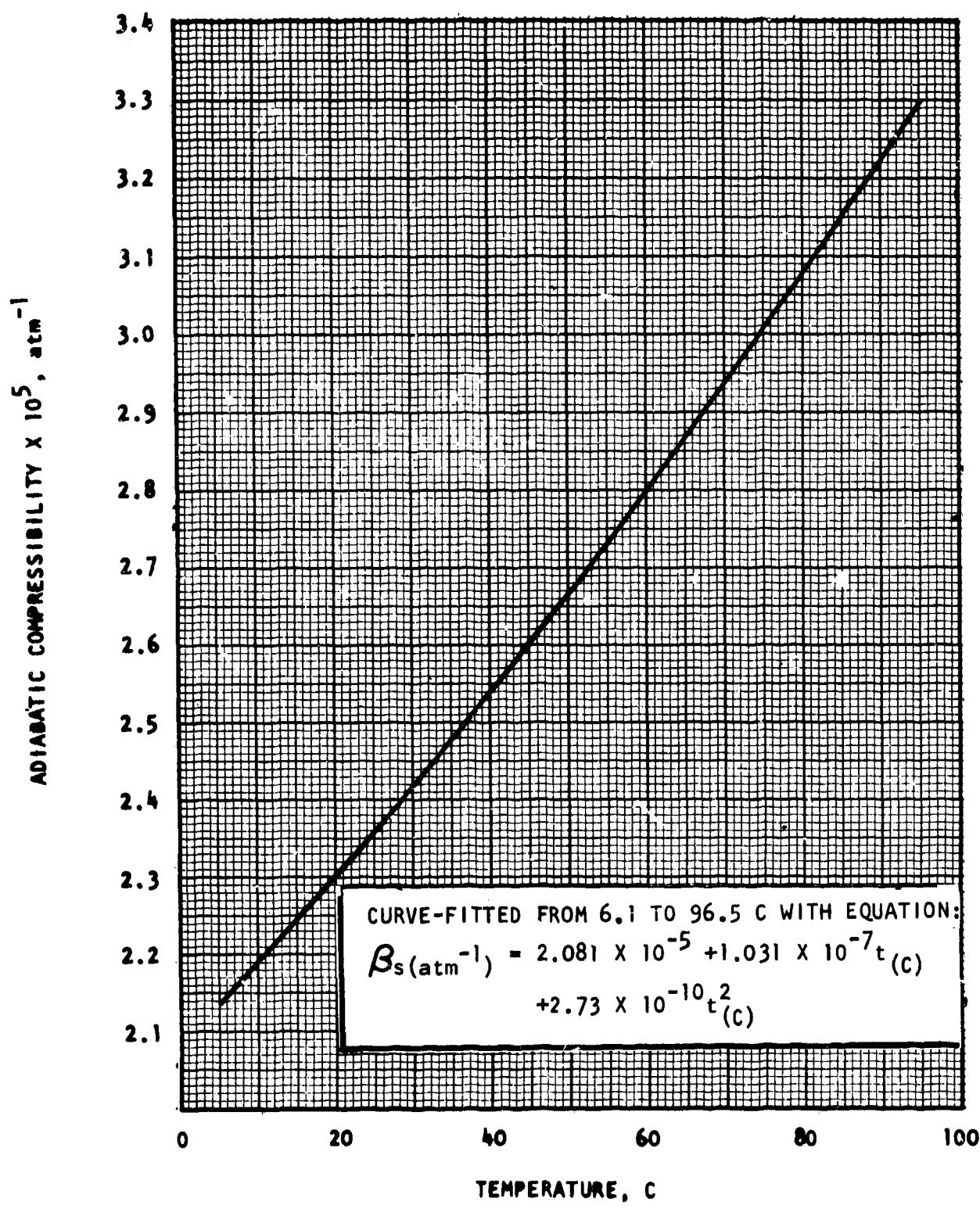


Figure 4. Adiabatic Compressibility of Liquid Hydrazine

$$\beta_s(\text{atm}^{-1}) = 4.182 \times 10^{-5} + 2.403 \times 10^{-7} t(\text{C}) + 8.848 \times 10^{-10} t(\text{C})^2 + 5.29 \times 10^{-12} t(\text{C})^3$$

and

$$\beta_s(\text{psi}^{-1}) = 2.572 \times 10^{-6} + 8.083 \times 10^{-9} t(\text{F}) + 1.266 \times 10^{-11} t(\text{F})^2 + 6.17 \times 10^{-14} t(\text{F})^3$$

The standard errors of estimate for these expressions are 2.22×10^{-8} atm^{-1} and 1.51×10^{-9} psi^{-1} , respectively.

(U) Adiabatic Compressibility of UDMH. A least squares computer program was used with the experimental sonic velocity and density data (Ref. 10) on unsymmetrical dimethylhydrazine [UDMH or $(\text{CH}_3)_2\text{N}_2\text{H}_2$] to calculate adiabatic compressibility over a temperature range of -37.3 to 93.0 C (-35.1 to 199.4 F). The resulting equations in the metric (represented graphically in Fig. 5) and English systems are:

$$\beta_s(\text{atm}^{-1}) = 6.729 \times 10^{-5} + 5.334 \times 10^{-7} t(\text{C}) + 2.800 \times 10^{-9} t(\text{C})^2 + 1.098 \times 10^{-11} t(\text{C})^3 + 1.243 \times 10^{-13} t(\text{C})^4$$

and

$$\beta_s(\text{psi}^{-1}) = 3.990 \times 10^{-6} + 1.669 \times 10^{-8} t(\text{F}) + 5.145 \times 10^{-11} t(\text{F})^2 + 2.488 \times 10^{-14} t(\text{F})^3 + 8.059 \times 10^{-16} t(\text{F})^4$$

The standard errors of estimate for these expressions are 3.99×10^{-6} atm^{-1} and 3.18×10^{-8} psi^{-1} , respectively.

(U) Adiabatic Compressibility of 50 N_2H_4 - 50 UDMH. The experimental sonic velocity data were combined with existing density data (Ref. 11) by means of a least squares computer program to obtain expressions for the adiabatic compressibility of the 50 N_2H_4 - 50 UDMH fuel blend over the temperature range of 0 to 75 C (32 to 167 F). The resulting metric (represented graphically in Fig. 6) and English system expressions are:

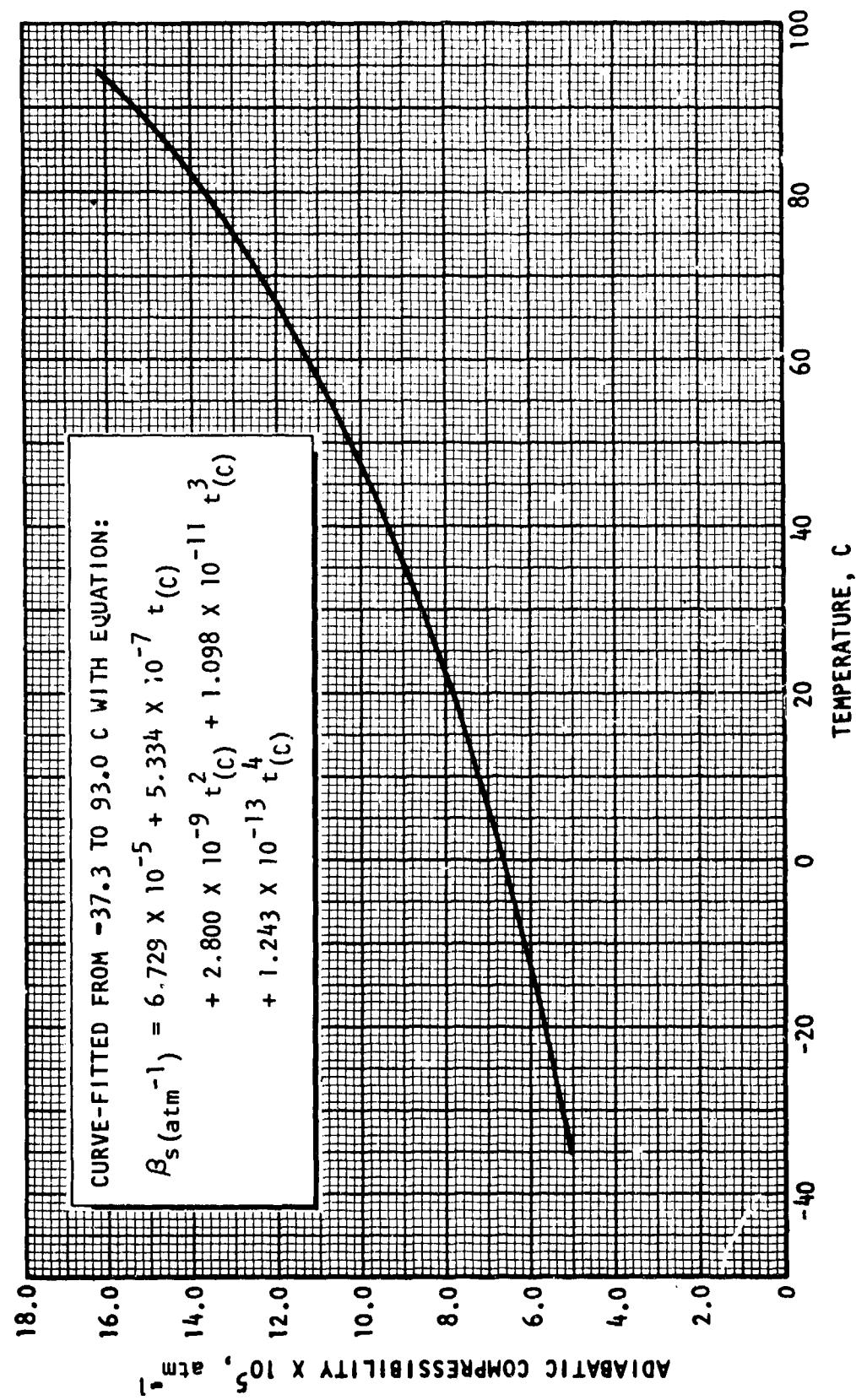


Figure 5. Adiabatic Compressibility of Liquid UDMH

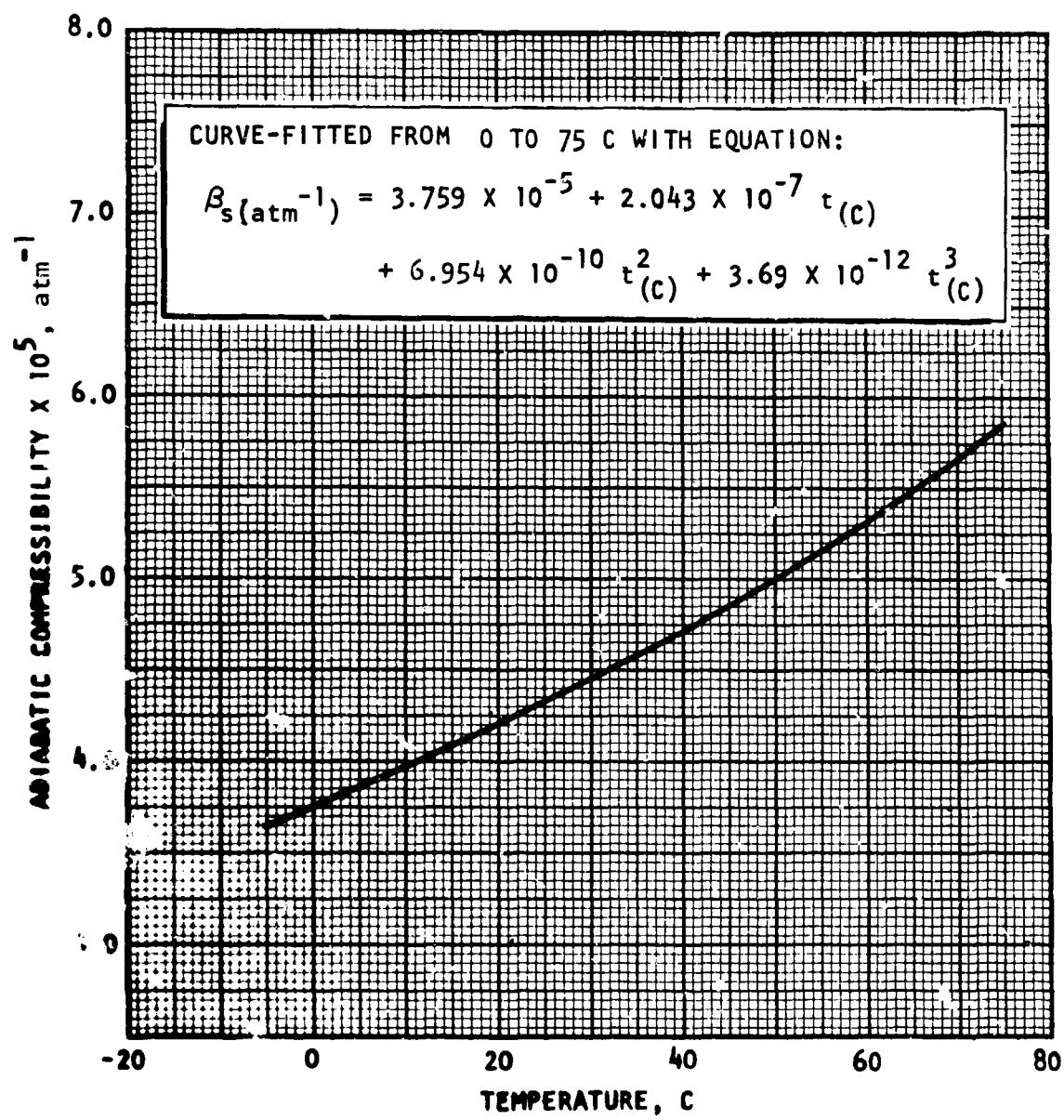


Figure 6. Adiabatic Compressibility of Liquid 50 N_2H_4 -50 UDMH

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$$\begin{aligned}\beta_s(\text{atm}^{-1}) &= 3.759 \times 10^{-5} + 2.043 \times 10^{-7}t_{(C)} + 6.954 \times 10^{-10}t_{(C)}^2 \\ &+ 3.69 \times 10^{-12}t_{(C)}^3\end{aligned}$$

and

$$\begin{aligned}\beta_s(\text{psi}^{-1}) &= 2.324 \times 10^{-6} + 6.922 \times 10^{-9}t_{(F)} + 1.047 \times 10^{-11}t_{(F)}^2 \\ &+ 4.310 \times 10^{-14}t_{(F)}^3\end{aligned}$$

(C) Adiabatic Compressibility of MHF-3. The experimental MHF-3 sonic velocity data were combined with MHF-3 density data (Ref. 6) by means of a least squares computer program to obtain the following expressions of MHF-3 adiabatic compressibility over a temperature range of -35.7 to 95.1 C (-32.3 to 203.2 F):

$$\begin{aligned}\beta_s(\text{atm}^{-1}) &= 3.822 \times 10^{-5} + 2.195 \times 10^{-7}t_{(C)} + 8.557 \times 10^{-10}t_{(C)}^2 \\ &+ 4.683 \times 10^{-12}t_{(C)}^3\end{aligned}$$

and

$$\begin{aligned}\beta_s(\text{psi}^{-1}) &= 2.352 \times 10^{-6} + 7.317 \times 10^{-9}t_{(F)} + 1.272 \times 10^{-11}t_{(F)}^2 \\ &+ 5.464 \times 10^{-14}t_{(F)}^3\end{aligned}$$

The standard errors of estimate of these expressions are $2.67 \times 10^{-8} \text{ atm}^{-1}$ and $1.82 \times 10^{-9} \text{ psi}^{-1}$, respectively. Figure 7 is a graphical illustration of the metric system expression.

(C) Adiabatic Compressibility of MHF-5. Using a least squares computer program, the MHF-5 sonic velocity data were utilized with MHF-5 density data (Ref. 6) to obtain expressions for the adiabatic compressibility of MHF-5 over the temperature range of -39.4 to 95.0 C (-39.0 to 203.0 F). The resulting equations in metric (represented graphically in Fig. 8) and English units are:

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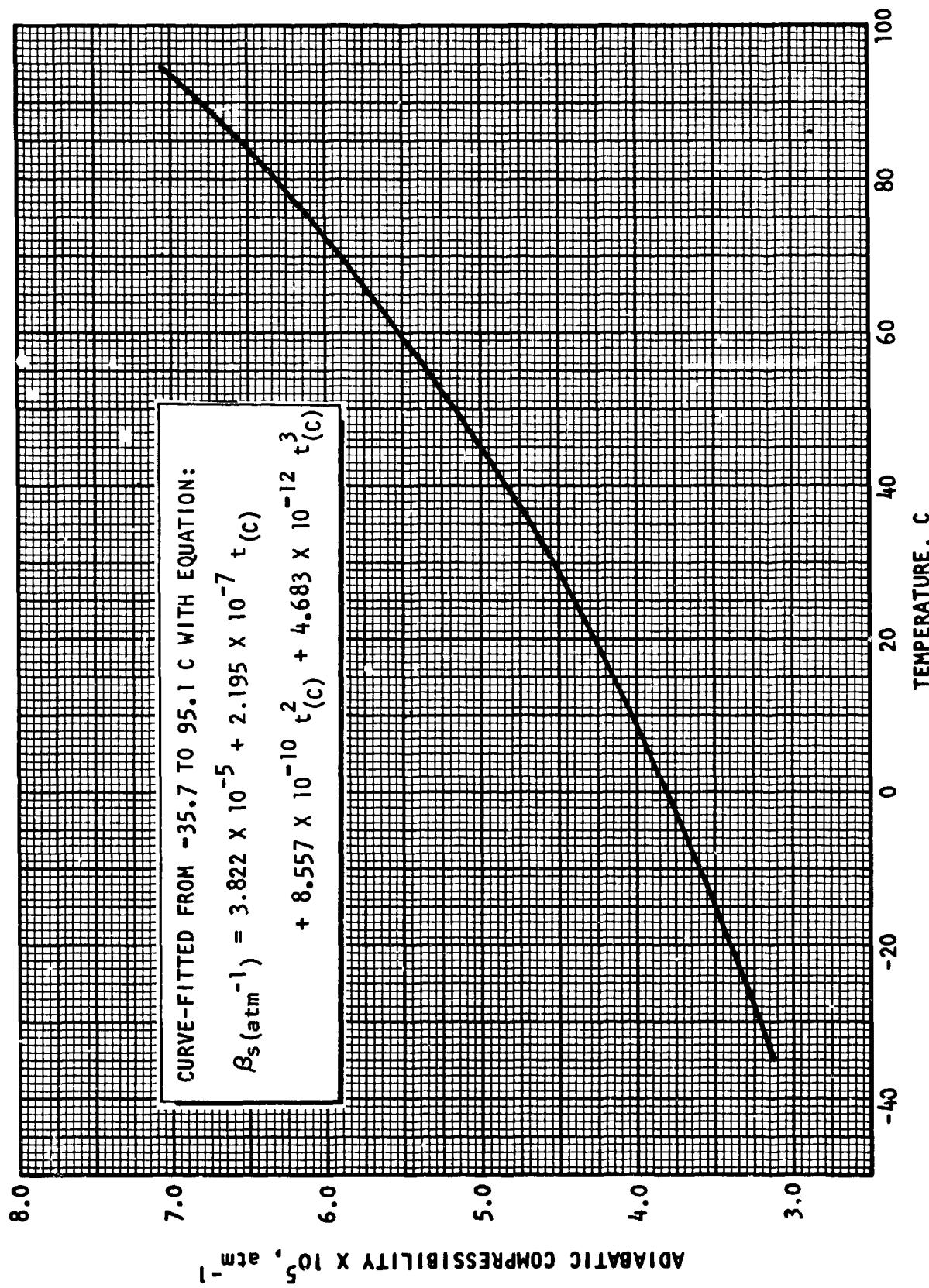


Figure 7. Adiabatic Compressibility of Liquid MHE-3

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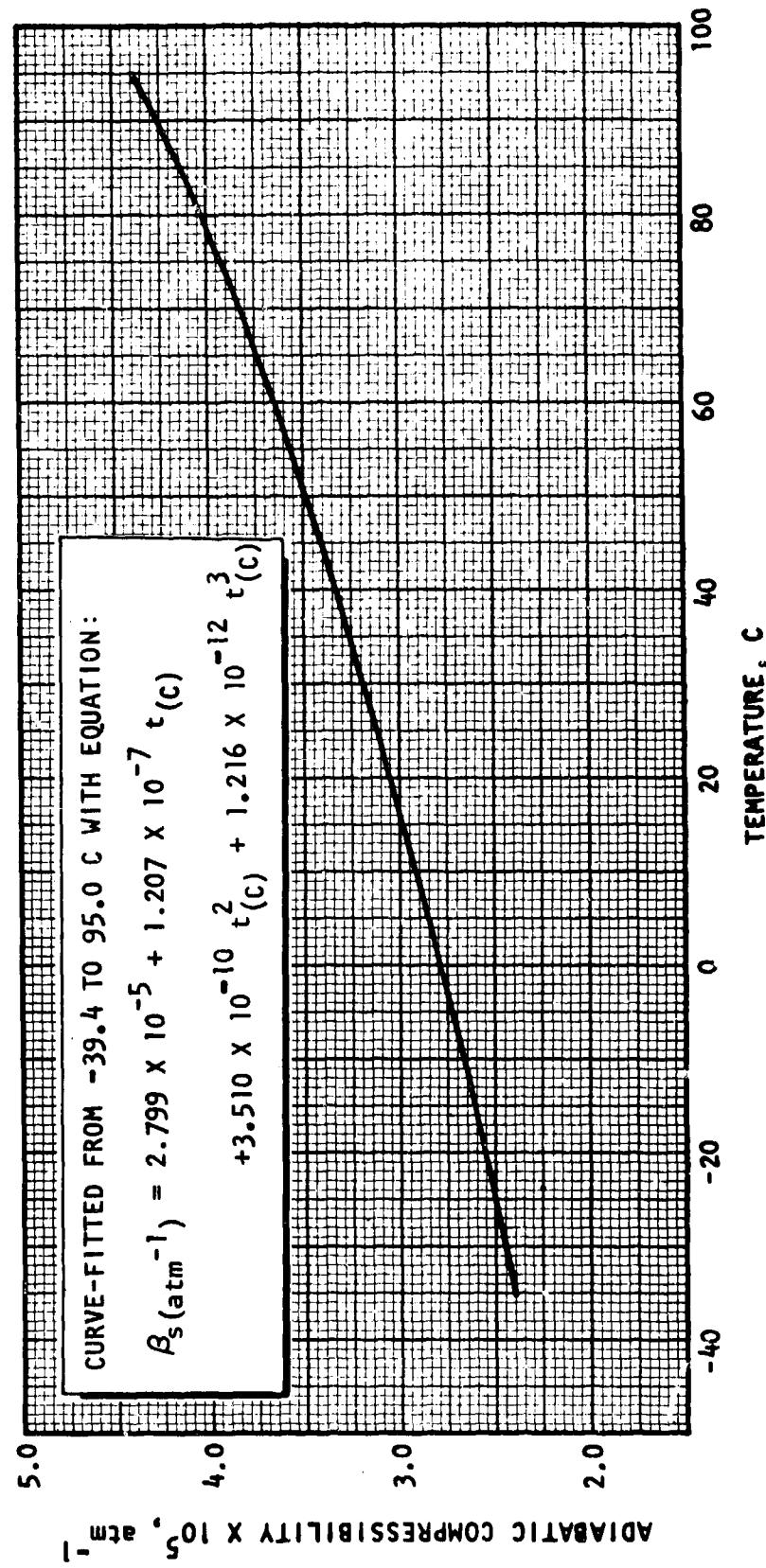


Figure 8. Adiabatic Compressibility of Liquid MFH-5

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$$(c) \quad \beta_s(\text{atm}^{-1}) = 2.799 \times 10^{-5} + 1.207 \times 10^{-7} t_{(C)} + 3.510 \times 10^{-10} t_{(C)}^2 + 1.216 \times 10^{-12} t_{(C)}^3$$

and

$$\beta_s(\text{psi}^{-1}) = 1.765 \times 10^{-6} + 4.136 \times 10^{-9} t_{(F)} + 6.010 \times 10^{-12} t_{(F)}^2 + 1.418 \times 10^{-14} t_{(F)}^3$$

The standard errors of estimate of these equations are $4.99 \times 10^{-9} \text{ atm}^{-1}$ and $3.40 \times 10^{-10} \text{ psi}^{-1}$, respectively.

(U) Adiabatic Compressibility of MHF-7. The experimental data from the sonic velocity and density measurements on the MHF-7 formulations were combined with similar data on MHF-3 and correlated by means of a least squares computer curve fit program with the following expressions of adiabatic compressibility (β) as a function of temperature (t) and concentration in weight percent (w/o) N_2H_4 (H) and H_2O (W):

$$\beta_s(\text{atm}^{-1}) = 4.2580 \times 10^{-5} + 2.7726 \times 10^{-7} t_{(C)} + 7.421 \times 10^{-10} t_{(C)}^2 - 3.735 \times 10^{-12} t_{(C)}^3 + 9.236 \times 10^{-14} t_{(C)}^4 - 3.040 \times 10^{-7} H_{(w/o)} - 4.056 \times 10^{-7} W_{(w/o)} - 3.255 \times 10^{-9} H_{(w/o)} t_{(C)} - 5.684 \times 10^{-9} W_{(w/o)} t_{(C)}$$

and

$$\beta_s(\text{psi}^{-1}) = 2.5800 \times 10^{-6} + 9.2716 \times 10^{-9} t_{(F)} + 2.345 \times 10^{-11} t_{(F)}^2 - 1.202 \times 10^{-13} t_{(F)}^3 + 5.986 \times 10^{-16} t_{(F)}^4 - 1.675 \times 10^{-8} H_{(w/o)} - 2.072 \times 10^{-8} W_{(w/o)} - 1.230 \times 10^{-10} H_{(w/o)} t_{(F)} - 2.149 \times 10^{-10} W_{(w/o)} t_{(F)}$$

The standard errors of estimate of these expressions, represented graphically for the nominal MHF-7 formulation in Fig. G-2 and G-2a of Appendix G, are $2.75 \times 10^{-7} \text{ atm}^{-1}$ and $1.87 \times 10^{-8} \text{ psi}^{-1}$, respectively.

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Surface Tension Measurements

- (U) Surface tension measurements were conducted on N_2O_4 and MON-25 over temperature ranges of -9.3 to 90.7 C (15.3 to 195.2 F) and -35.3 to 82.2 C (-31.5 to 180.0 F), respectively. The measurements were made through the use of a modified differential capillary rise technique, which involves determinations of the difference in rise of a liquid in two capillaries of different diameters. An experimental apparatus (shown in Fig. 9) previously used (Ref. 2) in surface tension measurements on MHF-3 and MHF-5, was used in measurements below 20 C (68 F), while a heavier-walled apparatus was used at temperatures above this level.
- (U) Each apparatus consists of two precision-bore pyrex capillaries sealed externally (thus minimizing error arising from optical distortion) to a sample reservoir. A 25X photomicrograph of each capillary was used to measure bore diameters and uniformity. A Fischer-Porter Teflon needle valve attached to the apparatus provided isolation of the hygroscopic propellant sample from the atmosphere. In addition, the propellant samples were loaded by means of a vacuum line. In this manner, measurements were made on the saturated liquid over the entire temperature range without contamination of the propellant by atmospheric moisture or loss of propellant at the higher temperatures.
- (U) During actual measurements, the surface tension apparatus was immersed in a constant temperature bath and aligned vertically with a plumb bob. After temperature equilibrium was attained at selected and regulated temperatures (by means of a constant temperature bath), the differential liquid rise in the capillaries was measured with a cathetometer. The equilibrium temperatures were measured with a 0.1 F precision thermometer for temperatures above 32 F (0 C), and a copper-constantan thermocouple for temperatures below 32 F. As a check and calibration of the technique

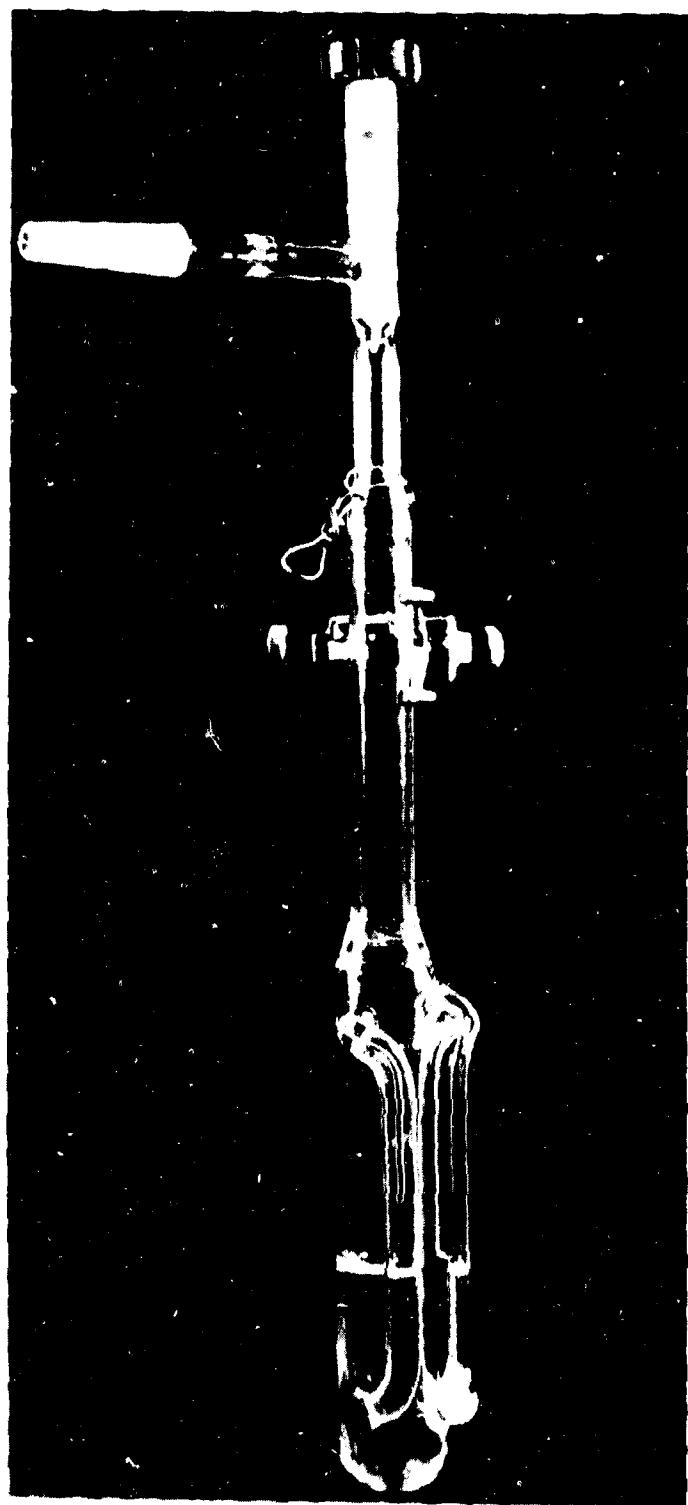


Figure 9. Bicapillary Surface Tension Apparatus

and apparatus, the surface tensions of distilled water, methylcyclohexane, and benzene (doubly distilled over sodium) were measured and found to be within 1.5 percent of the accepted literature values. Using the calibrated apparatus constants and the measured values for liquid rise, the surface tensions of the test fluids were calculated by the following equation:

$$\gamma = g(\rho_l - \rho_v)(h_2 - h_1)/2 \left(\frac{1}{r_1} - \frac{1}{r_2} \right)$$

where

g = gravity constant
 $\rho_l - \rho_v$ = density difference between liquid and vapor
 $h_2 - h_1$ = difference of rise in capillaries
 r_1, r_2 = radii of capillaries

(U) Surface Tension of N_2O_4 . Using the bicapillary surface tension devices described above, surface tension measurements were made on nitrogen tetroxide (N_2O_4) over the range of -9.3 to 90.7 C (15.3 to 195.2 F). The surface tension was calculated and curve fit with a least squares computer program. Liquid and vapor densities used in the reduction of the experimental data were obtained from Rocketdyne's previous (Ref. 2) evaluation and correlation of available literature values. The resulting data (Table 11) are represented by the following equations:

$$\gamma \text{ (dynes/cm)} = 30.07 - 0.207 t(C) + 3.0 \times 10^{-4} t(C)^2$$

and

$$\gamma \text{ (lbs/ft)} = 2.319 \times 10^{-3} - 8.29 \times 10^{-6} t(F) + 6.4 \times 10^{-9} t(F)^2$$

TABLE 11
SURFACE TENSION DATA ON SATURATED LIQUID N_2O_4 *^{*}

Temperature		Surface Tension, dynes/cm		Surface Tension, 1bs/ft x 10 ³ (Calculated)
C	F	Observed	Calculated	
- 9.3	15.3	31.80	32.02	2.194
- 5.2	22.6	31.10	31.16	2.135
0.0	32.0	30.11	30.07	2.061
7.0	42.6	29.01	28.86	1.978
10.1	50.1	28.21	28.02	1.920
12.4	54.3	27.86	27.55	1.888
13.3	55.9	27.53	27.38	1.876
15.8	60.4	27.14	26.88	1.842
18.1	64.6	26.33	26.42	1.810
21.4	70.5	25.51	25.78	1.767
26.1	79.0	24.00	24.87	1.704
30.1	86.2	23.96	24.11	1.652
36.0	96.8	22.85	23.01	1.577
40.0	104.0	22.35	22.27	1.526
46.1	115.0	20.95	21.16	1.450
50.6	123.1	20.52	20.36	1.395
53.5	128.3	20.35	19.86	1.360
56.1	133.0	20.00	19.40	1.329
61.1	141.9	18.59	18.55	1.271
65.7	150.2	17.81	17.77	1.218
70.9	159.7	16.72	16.90	1.158
74.7	166.4	15.89	16.29	1.116
78.8	173.8	15.50	15.63	1.071
82.0	179.6	15.11	15.12	1.036
85.6	186.0	14.60	14.56	0.9978
90.7	195.2	13.90	13.77	0.9438

*Sample Composition:

N_2O_4 , w/o	99.40
N_0 , w/o	0.58
H_2O , w/o	0.008
$NOCl$, w/o	<0.01

The standard errors of estimate for these equations are 0.30 dynes/cm and 2.0×10^{-5} lbs/ft, respectively. A graphical representation of these correlations is presented in Fig. 10 in metric units.

(U) Surface Tension of MON-25. Surface tension measurements were conducted initially on a MON-25 sample received from AFRPL over the temperature range of -35.3 to 82.2 C (-31.5 to 180.0 F). When computer analysis of the initial data revealed that four data points were significantly lower than that predicted by the majority of the data, it was assumed that this behavior was caused by the loss of N0 and/or fractional distillation of the sample in the upper portion of the apparatus. As a result, another run was conducted over the temperature range of 0.0 to 80.4 C (32.0 to 176.8 F) to obtain additional data in the affected measurement regions. All of the surface tension data were then calculated and curve fit using a least squares computer program. The liquid and vapor density data used in these calculations were obtained from Rocketdyne's evaluation and correlation of available literature values (Appendix C). It was assumed that the ideal gas law is valid for vapor densities and that the contact angle is negligible. The resulting data (presented in Table 12 with the sample composition) are represented by the following equations:

$$\gamma \text{ (dynes/cm)} = 30.65 - 0.1519 t_{(C)} - 4.89 \times 10^{-4} t_{(C)}^2$$

and

$$\gamma \text{ (lbs/ft)} = 2.275 \times 10^{-3} - 5.121 \times 10^{-6} t_{(F)} - 1.03 \times 10^{-8} t_{(F)}^2$$

The standard errors of estimate for these equations, which are graphically represented in Fig. C-5 and C-5a of Appendix C, are 0.32 dynes/cm and 2.2×10^{-5} lbs/ft, respectively.

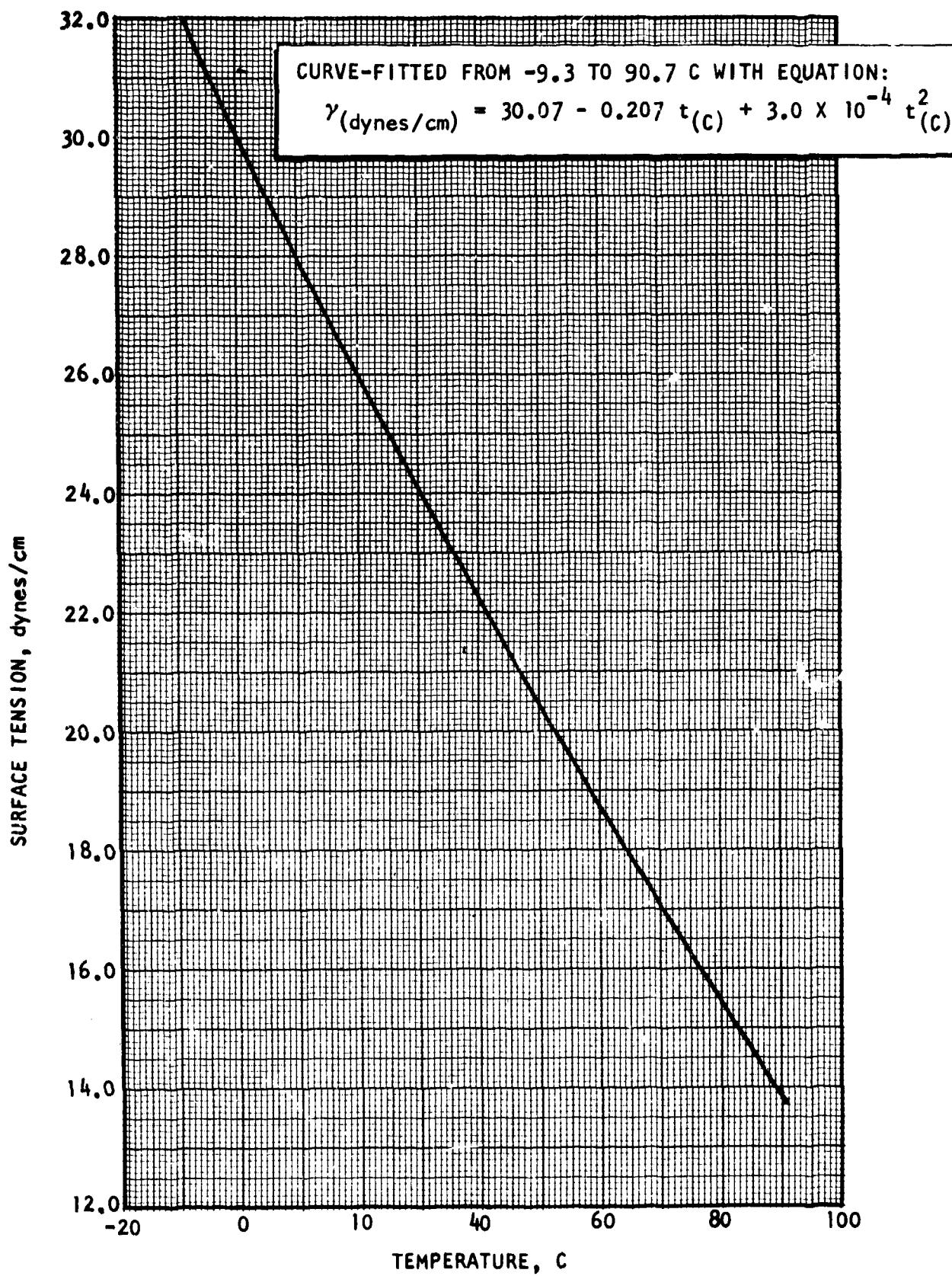


Figure 10. Surface Tension of Saturated Liquid N_2O_4

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TABLE 12

SURFACE TENSION DATA ON SATURATED LIQUID MON-25*

Temperature		Surface Tension, dynes/cm		Surface Tension 1b/ft x 10 ³ (Calculated)
C	F	Actual	Calculated	
-35.3	-31.5	35.35	35.40	2.426
-31.4	-24.5	35.37	34.94	2.394
-19.4	-2.9	33.37	33.41	2.290
-17.0	1.9	32.60	33.09	2.268
-12.0	10.4	32.27	32.40	2.220
-2.8	27.0	31.52	31.07	2.129
0.0	32.0	30.13	30.65	2.100
0.0	32.0	31.12	30.65	2.100
5.6	42.1	29.51	29.78	2.041
19.3	66.7	27.50	27.54	1.887
19.9**	67.8	25.32**	-	--
20.6	69.1	26.97	27.31	1.872
29.3	84.7	26.18	25.78	1.767
29.4	84.9	25.98	25.76	1.765
40.4	104.7	23.65	23.72	1.625
40.5	104.9	23.84	23.70	1.624
46.0	114.8	22.45	22.63	1.551
51.7	125.1	21.66	21.49	1.473
57.6	135.7	20.36	20.28	1.390
63.2	145.8	18.70	19.10	1.309
63.3	145.9	19.43	19.08	1.307
71.3**	160.3	15.43**	-	-
74.6	166.3	16.36	16.60	1.137
76.8**	170.2	14.62**	-	-
80.4	176.7	15.36	15.28	1.047
82.2**	180.0	14.04**	-	-

*Sample Composition:

N ₂ O ₄ , w/o	75.3
NO, w/o	24.7

**Suspect measurements
eliminated from data
correlation.

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Heat of Vaporization

(U) The latent heats of vaporization of IMDFNA, Florox, MOR-5, and MHF-7 were calculated from the slopes of their vapor pressure equations at their normal boiling points by means of the following correlation:

$$\frac{d \ln P}{d \left(\frac{1}{T} \right)} = - \frac{\Delta H_v}{R}$$

This correlation assumes that the vapor obeys the ideal gas law.

(U) Heat of Vaporization of IMDFNA. The heat of vaporization of IMDFNA (54.3 w/o HNO_2 - 44.3 w/o NO_2 - 0.33 w/o NO - 0.27 w/o H_2O - 0.8 w/o HF) was calculated as 7.606 Kcal/g-mole (13,691 Btu/lb-mole) at 24.4 C (75.9 F).

(C) Heat of Vaporization of Florox. The heat of vaporization of Florox, ClF_3^0 , (99.7 w/o ClF_3^0 , 0.1 w/o ClF_3 - 0.1 w/o FClO_2 - 0.1 w/o HF) was calculated as 7.000 Kcal/g-mole (12,600 Btu/lb-mole) at 30.6 C (87.1 F).

(C) Heat of Vaporization of MOR-5. The heat of vaporization of MOR-5 (78.3 w/o ClF_3^0 - 19.8 w/o ClF_5 - 1.6 w/o ClF_3 - 0.2 w/o FClO_2 - 0.1 w/o HF) was calculated as 5.969 Kcal/g-mole (10,744 Btu/lb-mole) at 9.4 C (48.9 F).

(U) Heat of Vaporization of MHF-7. The heat of vaporization of the nominal MHF-7 formulation (81 w/o $\text{CH}_3\text{N}_2\text{H}_3$ - 14 w/o N_2H_4 - 5 w/o H_2O) was calculated as 8.944 Kcal/g-mole (16,099 Btu/lb-mole) at 87.4 C (189.3 F). The heat of vaporization of the MHF-7 formulations was found to be independent of composition at the normal boiling point.

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Specific Heat Measurements

- (U) Experimental determinations of liquid propellant specific heats were conducted in an adiabatic calorimeter previously developed and utilized under Contracts AF04(611)-9563 (Ref. 12), AF04(611)-10546 (Ref. 1), and AF04(611)-11407 (Ref. 2). During this program, specific heat measurements were made on MON-25, Florox, MOR-5, and MHF-7.
- (U) The adiabatic calorimeter (whose successive development is described in detail in Ref. 12, 1, and 2) consists of an outer copper jacket surrounding an electrically heated, highly polished copper (adiabatic) shield, which is suspended by cotton thread from the copper ring attached to the lid of the calorimeter. A large sample container is suspended in the center of the heat shield by cotton thread attached to the heat shield lid. In this design, a differential thermocouple is used to monitor the temperature difference between the shield and the sample container. Electrical interaction between the differential thermocouple circuit and the sample thermocouple (which was a major problem in the apparatus initially utilized in Ref. 12) was prevented by insertion of a thin piece of lens paper between the differential thermocouple junctions and the surfaces to which they are attached (with GE varnish).
- (U) A block diagram of the electrical circuitry is shown in Fig. 11. In this circuit, the signal from the differential thermocouple is fed to a d-c microvolt amplifier, and then to a recorder and a current adjusting-type (CAT) control unit. This CAT unit continuously feeds the necessary power (by means of a silicon-controlled-rectifier power supply) into the shield (which is noninductively wound with constantan wire). The controller is set to regulate the shield temperature at various small temperature increments above that of the sample container to compensate for heat losses through the container leads to the heat sink (a constant-temperature bath

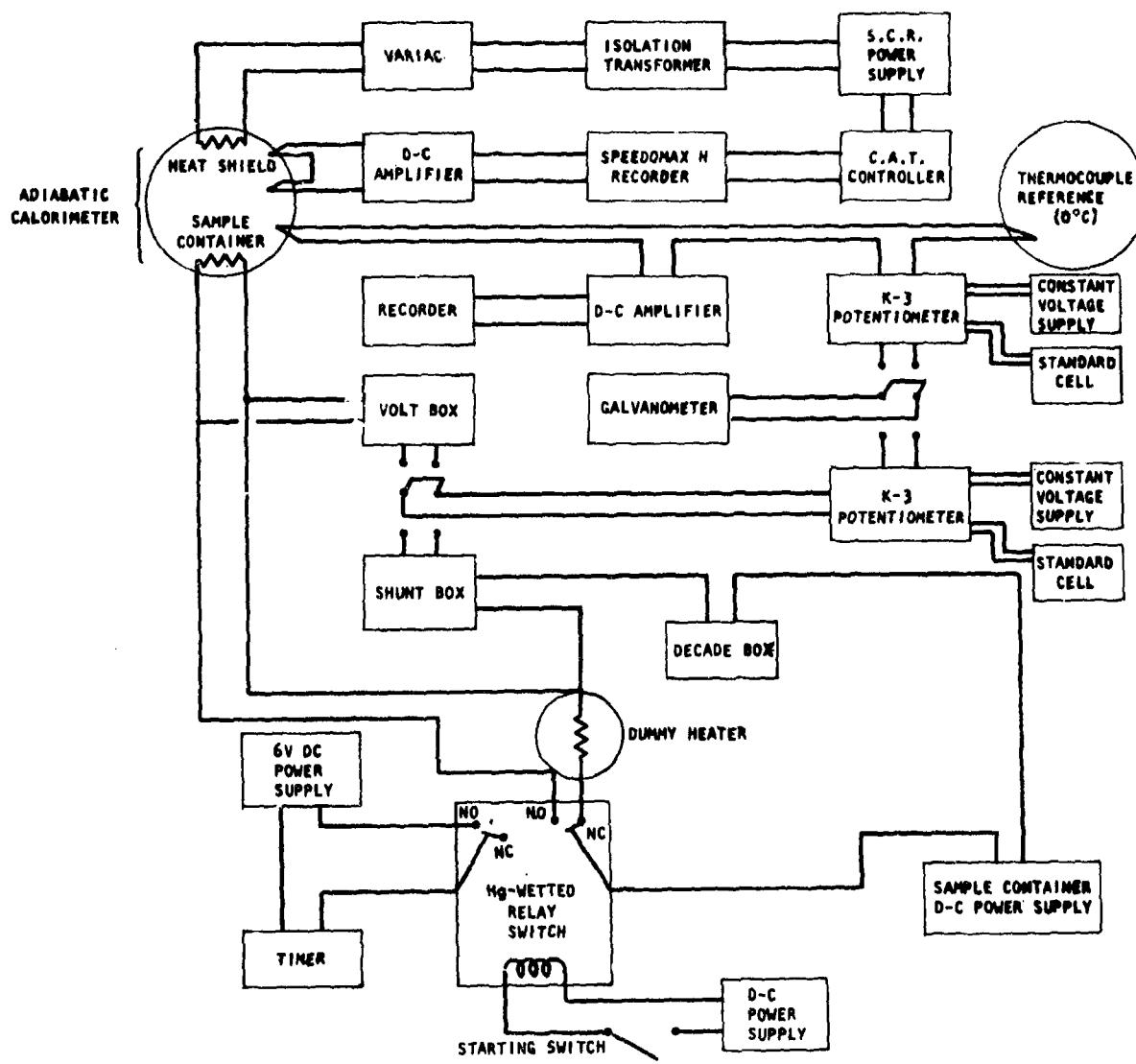


Figure 11. Block Diagram of the Circuit Used in Specific Heat Measurements

in which the calorimeter is immersed). The heat shield's associated equipment is housed in a console.

- (U) A constant current/voltage d-c power supply is used to heat the sample container. The energy supplied to the container is accurately determined by means of a K-3 potentiometer in line with a galvanometer. The temperature rise of the sample container and its contents is measured with a copper-constantan thermocouple whose output is recorded through use of another K-3 potentiometer in conjunction with a d-c microvolt amplifier and a recorder.
- (U) During specific heat measurements, the calorimeter was completely immersed in a regulated temperature bath. Two different bath media (dry ice-methanol and ice water), which provide the calorimeter with a constant-temperature heat sink, were generally required in the measurements to span the desired temperature ranges. A specially fabricated Teflon gasket is used as the seal between the calorimeter lid and the jacket. In addition, an NRC type 507 ionization gage is incorporated in the calorimeter apparatus to provide better measurements of the vacuum in the locale of the sample container.
- (U) Under this program, the supporting vacuum system for the calorimeter was upgraded. To improve the system, a new vacuum line, shorter in length and larger in cross-section, was fabricated to replace the one previously used. A large LN_2 trap was placed on the vacuum line near the calorimeter with the line plumbed to an oil diffusion pump (together with a roughing pump) which were housed in a fume hood as a safety precaution. Since this revampment, the vacuum system pressure can be maintained below 10^{-4} mm Hg.

(U) When the previously fabricated (container No. 5 in Ref. 2) oxidizer sample container developed a leak during initial specific heat measurements on Florox, that precluded repair and reuse of the container, two new sample containers were fabricated. These containers are cylindrical in shape and fabricated of copper with a re-entrant well (for the thermocouple) entering through the bottom plate and a filling tube extending from the top plate. The various parts were assembled and sealed principally by electron-beam welding with four fins brazed (with silver solder) lengthwise on the inside surface of the outer wall. Because stainless steel is not as adaptable as monel to electron-beam welding with copper, the bottom plates of the new containers were constructed of monel 402 (its low conductivity restricts thermal conduction from the outer wall across the bottom to the re-entrant well). For an unknown reason, one of the new bottom plates fissured during a second electron-beam welding attempt after an initial welding was unsuccessful. However, the damaged plate was removed and a new one was satisfactorily welded to the container. After the containers were found to be helium-leak-tight at ambient and low temperatures, they were noninductively wound with No. 30 B&S gage constantan wire, coated with GE varnish, and wrapped with copper foil.

(U) A new aluminum sample container was also fabricated for measurements on MON-25, because of the problems which could have resulted from corrosion of the copper (type OFHC) container by the MON-25. The container was fabricated principally from 2219 Al with electron-beam welded joints. Since there was evidence that the 2219 Al would fissure when crimped, the filling tube was fabricated from 1100 Al. (Both of these materials were found to be compatible from immersion tests in MON-25 at 165 F.) In addition, to determine if energy-absorbing or -releasing transitions occur in 2219 Al over the temperature range of interest in the MON-25 heat capacity measurements, a Perkin-Elmer differential scanning calorimeter was used to run differential thermal analyses (DTA) on selected

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samples of the alloy. The DTA tests included runs conducted on samples of 2219 Al, electron-beam welded 2219 Al, electron-beam welded 2219 Al after 88 hours contact with MON-25, and the latter after annealing at 108 C (226 F) for 17 hours. In no case did the thermal data exhibit any transitions which would preclude the use of 2219 Al in calorimetric determinations. After fabrication and leak checks with helium, the aluminum sample container was noninductively wound with No. 30 B&S gage constantan wire, coated with GE varnish, and wrapped with copper foil.

(U) In the treatment of the data from the specific heat measurements, the amount of electrical energy added to the calorimeter was calculated from the equation:

$$H = i^2 R t$$

where

H = electrical energy, joules

i = current

R = E/i

t = time, seconds

(U) The specific heat (C_s) of the saturated liquid was then derived from the measured change in temperature caused by this addition of electrical energy:

$$C_s = \left[(H/\Delta T)_{\text{sample}} - H_C \right] / \text{wt sample}$$

where

ΔT = temperature rise determined from a plot of temperature vs time by extrapolating to the midpoint of the heating curve

H_C = calorimeter constant

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(c) Specific Heat of Florox. Recalibration of sample container No. 5 following the vacuum system revampment was successfully completed over the temperature range of 23.6 to 58.3 C (74.5 to 136.9 F) resulting in a linear heat capacity-temperature curve with point scatter well within ± 0.5 percent. Following this check of the calorimeter system, the calorimeter was disassembled and the sample container attached to a vacuum line and passivated using Florox (ClF_3O) vapor at 200 to 400 mm Hg pressure. Although noncondensables were detected following the initial passivation, several checks of the container using a Heise gage in the system failed to indicate any leaks. Also, the integrity of this particular container had been verified by previous usage (Ref. 2), which included helium leak tests and a successful experimental run with a similar oxidizer. On this basis, the passivation was continued, and its effectiveness indicated by negligible detection of noncondensables during the last in the series of passivations. After being loaded with 102.8 grams of ClF_3O and the filling tube sealed with soft solder, the sample container was placed in the calorimeter. However, overnight evacuation of the system failed to produce the required vacuum, and a small quantity of a yellow condensable was found in the LN_2 trap. The calorimeter was carefully disassembled and, when tests indicated a leak in the body of the sample container, it was unloaded. Through use of a dry box and a vacuum line, approximately 102.3 grams of ClF_3O were reclaimed from the sample container. Infrared and gas chromatographic analyses indicated negligible decomposition of the reclaimed ClF_3O . When helium leak tests indicated that a leak within the container re-entrant well was nonrepairable, fabrication of two new sample containers was initiated.

(c) One of the new sample containers was loaded with helium and calibrated over the temperature range of -46.6 to 56.6 C (-51.5 to 133.9 F) resulting in a 42-point heat capacity/temperature curve (which was linear

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(C) up to 40 C). Average point scatter was within \pm 0.5 percent. Following this calibration, the calorimeter was disassembled and the container passivated with ClF₃0 vapor. After passivation, 112.1 grams of ClF₃0 were transferred with a vacuum line by volume expansions to the container packed in dry ice. The filling tube was crimped off and sealed with soft solder. After loading the container into the calorimeter and outgassing several days, the experimental measurements were initiated.

(C) During specific heat measurements on saturated liquid ClF₃0, fifty-three individual data points (listed in Table 13) were obtained over the temperature range of -39.47 to 39.04 C (-39.05 to 102.27 F). A least squares computer curve-fit of the data produced the following linear expressions:

$$C_s(\text{cal/g-C}) = 0.3079 + 1.37 \times 10^{-4}t(\text{C})$$

and

$$C_s(\text{Btu/lb-F}) = 0.3055 + 7.60 \times 10^{-5}t(\text{F})$$

(C) The standard errors of estimate of these curve-fits (graphically represented in Fig. E-4 and E-4a in Appendix E) are 0.003 cal/g-C (Btu/lb-F). The post-run weight of the loaded container was within 0.01 grams of its pre-run weight. Post-run analysis of the reclaimed ClF₃0 sample by a combination of IR spectrophotometry and gas chromatography indicated negligible decomposition; the composition of the sample is given in Table 13.

(C) Specific Heat of Liquid MOR-5. Following the specific heat measurements on ClF₃0, similar measurements were conducted on the MOR-5 oxidizer blend (nominal composition: 78 w/o ClF₃0 - 22 w/o ClF₅). Attachment of a new

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TABLE 13

EXPERIMENTAL SPECIFIC HEAT DATA ON
SATURATED LIQUID FLOROX*

Temperature		Specific Heat, cal/g-C	Temperature		Specific Heat, cal/g-C
C	F		C	F	
-39.47	-39.05	0.302	-0.60	30.92	0.307
-38.53	-37.35	0.309	1.18	34.12	0.307
-36.82	-34.28	0.306	2.96	37.33	0.306
-35.10	-31.18	0.300	4.73	40.51	0.308
-34.54	-30.17	0.299	6.48	43.66	0.307
-33.38	-28.08	0.309	7.03	44.65	0.314
-32.78	-27.00	0.304	8.72	47.70	0.307
-30.80	-23.44	0.303	10.43	50.77	0.309
-29.04	-20.27	0.301	12.13	53.83	0.310
-27.27	-17.09	0.305	13.83	56.89	0.307
-26.40	-15.52	0.304	15.54	59.97	0.309
-25.53	-13.95	0.304	17.24	63.03	0.310
-24.67	-12.41	0.301	18.95	66.11	0.309
-23.78	-10.80	0.307	20.66	69.19	0.310
-22.95	-9.31	0.309	22.36	72.25	0.309
-21.22	-6.20	0.299	23.78	74.80	0.315
-19.50	-3.10	0.306	24.06	75.31	0.315
-17.78	0.00	0.303	25.49	77.88	0.308
-16.06	3.09	0.304	27.20	80.96	0.313
-14.82	5.32	0.312	28.89	84.00	0.314
-13.05	8.51	0.308	30.59	87.06	0.312
-11.28	11.70	0.307	32.28	90.10	0.312
-9.49	14.92	0.301	33.97	93.15	0.314
-7.71	18.12	0.308	35.65	96.17	0.317
-5.93	21.33	0.309	37.35	99.23	0.309
-4.15	24.53	0.305	39.04	102.27	0.315
-2.37	27.73	0.309			

*Sample Composition:

ClF_3 0, w/o	99.7
FClO_2 + ClF_3 , w/o	0.2
HF, w/o	0.1

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(C) filling tube to the sample container was necessary when the old tube was appreciably shortened during ClF_3O unloading operations because of prior plugging of the tube by solder. The new tube was attached with soft solder rather than silver brazing, because the highly conductive container proved to be too great a heat sink for brazing operations. A dimpling technique was developed to reduce the possibility of solder plugging the filling tube during future tube-capping operations. After sample analysis of the composition by gas chromatography and IR spectrophotometry, the remaining sample (114.1 grams) was loaded by vacuum line into the sample container. The filling tube was dimpled, crimped off, and capped with soft solder, and the container was loaded into the calorimeter.

(C) Specific heat measurements on the MOR-5 oxidizer blend (the actual composition, which was slightly rich in ClF_5 , is shown in Table 14) were successfully completed over the temperature range of -44.85 to 35.54 C (-48.73 to 95.97 F). A least squares computer curve-fit correlation of 44 data points, listed in Table 14, resulted in the following expressions of saturated specific heat as a function of temperature:

$$C_s(\text{cal/g-C}) = 0.298 + 2.0 \times 10^{-4}t(\text{C})$$

and

$$C_s(\text{Btu/lb-F}) = 0.295 + 1.1 \times 10^{-4}t(\text{F})$$

(U) The standard errors of estimate of these curve fits (represented graphically in Fig. F-4 and F-4a of Appendix F) are 0.0025 cal/g-C (Btu/lb-F). The data for the mixture appear to deviate negatively from that expected for an ideal mixture (e.g., at 0 C, the experimental value is ~2 percent less than that calculated from additive contributions of the component specific heats).

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TABLE 14

EXPERIMENTAL SPECIFIC HEAT DATA
ON SATURATED LIQUID MOR-5

Temperature		Specific Heat, cal/g-C	Temperature		Specific Heat, cal/g-C
C	F		C	F	
-44.85	-48.73	0.293	-7.02	19.36	0.298
-44.72	-48.50	0.289	-4.90	23.18	0.296
-42.84	-45.11	0.294	-2.80	26.96	0.297
-40.33	-40.59	0.286	-0.69	30.76	0.297
-38.44	-37.19	0.293	1.41	34.54	0.297
-36.57	-33.83	0.295	3.51	38.32	0.296
-34.69	-30.44	0.288	5.60	42.08	0.297
-32.81	-27.06	0.292	7.68	45.82	0.302
-30.94	-23.69	0.291	9.49	49.08	0.304
-29.06	-20.31	0.289	11.72	53.10	0.295
-27.18	-16.92	0.294	13.92	57.06	0.300
-25.31	-13.56	0.291	16.10	60.98	0.301
-24.97	-12.95	0.294	18.30	64.94	0.299
-22.93	-9.27	0.294	19.32	66.78	0.305
-20.89	-5.60	0.296	20.50	68.90	0.302
-18.85	-1.93	0.291	22.69	72.84	0.302
-17.72	0.10	0.295	24.88	76.78	0.301
-16.04	3.13	0.296	26.95	80.51	0.308
-14.35	6.17	0.298	29.11	84.40	0.306
-12.62	9.28	0.295	31.26	88.27	0.306
-10.88	12.42	0.295	33.41	92.14	0.307
-9.12	15.56	0.299	35.54	95.97	0.308

*Sample Composition:

	<u>Pre-Run</u>	<u>Post-Run</u>	
$\text{C1F}_3\text{O}$, w/o	75.3	$\text{C1F}_3\text{O}$, w/o	75.6
C1F_5 , w/o	24.0	C1F_5 , w/o	23.9
C1F_3 , w/o	0.4	C1F_3 , w/o	0.3
FC1O_2 , w/o	0.2	FC1O_2 , w/o	0.1
HF, w/o	< 0.1	HF, w/o	< 0.1

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(U) Specific Heat of MON-25. Following calibration of the helium-loaded (1 atmosphere at room temperature) aluminum sample container over the temperature range of -62.7 to 64.4 C (-80.9 to 147.9 F), the sample container was filled with 48.90 g of MON-25 by means of a vacuum line and sealed. Forty-six specific heat measurements were conducted on the MON-25 sample over a temperature range of -48.7 to 52.8 C (-55.7 to 127.0 F). The results, given in Table 15 with the sample analysis, were correlated by a least squares computer curve-fit program with the following equations:

$$C_s(\text{cal/g-C}) = 0.412 + 7.1 \times 10^{-4}t(\text{C}) + 6.8 \times 10^{-6}t(\text{C})^2$$

and

$$C_s(\text{Btu/lb-F}) = 0.401 + 2.6 \times 10^{-4}t(\text{F}) + 2.1 \times 10^{-6}t(\text{F})^2$$

The standard errors of estimate for these expressions, represented graphically in Fig. C-6 and C-6a of Appendix C, are 0.003 cal/g-C (Btu/lb-F).

(U) Specific Heat of MHF-7. Specific heat measurements were conducted on MHF-7 using a copper sample container previously employed in specific heat measurements on NOTSGEL A (Ref. 13). After recalibration of the empty container over a temperature range of -55 to 66 C (-67 to 150.8 F), specific heat measurements were conducted on three MHF-7 formulations (the -N, -1, and -2 formulations described in the "Propellant Formulation and Chemical Analysis" section). The data from these measurements and previous (Ref. 2) measurements on MHF-3 (shown in Table 16 with the sample analyses) were correlated by a least squares curve-fit computer

TABLE 15

EXPERIMENTAL SPECIFIC HEAT DATA ON SATURATED LIQUID MON-25*

Temperature		Specific Heat, (cal/g-C) or (Btu/lb-F)	Temperature		Specific Heat (cal/g-C) or (Btu/lb-F)
C	F		C	F	
-48.7	-55.7	0.390	1.5	34.7	0.413
-45.9	-50.6	0.393	4.3	39.7	0.415
-43.2	-45.8	0.393	7.0	44.6	0.423
-41.7	-43.1	0.394	9.8	49.6	0.418
-40.4	-40.7	0.388	12.5	54.5	0.419
-38.8	-37.8	0.390	15.2	59.4	0.429
-37.7	-35.9	0.399	18.8	65.8	0.423
-36.8	-34.2	0.398	21.6	70.9	0.428
-36.1	-33.0	0.396	24.3	75.7	0.432
-34.1	-29.4	0.399	27.0	80.6	0.433
-33.5	-28.3	0.397	27.8	82.0	0.434
-30.9	-23.6	0.395	30.4	86.7	0.438
-28.3	-18.9	0.395	32.3	90.1	0.442
-24.7	-12.5	0.400	32.9	91.2	0.443
-21.8	-7.2	0.399	35.3	95.5	0.445
-18.9	-2.0	0.402	37.7	99.9	0.445
-16.1	3.0	0.406	38.3	100.9	0.442
-13.2	8.2	0.407	40.3	104.5	0.450
-10.3	13.5	0.402	41.3	106.3	0.454
-7.5	18.5	0.412	44.2	111.6	0.456
-4.7	23.5	0.409	47.1	116.8	0.464
-4.0	24.8	0.409	50.0	122.0	0.470
-1.2	29.8	0.416	52.8	127.0	0.474

*Sample Composition:

N_2O_4 , w/o	75.3
NO, w/o	24.7

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TABLE 16

EXPERIMENTAL SPECIFIC HEAT DATA ON MHF-7 FORMULATIONS

Formu- lation*	Temperature		Specific Heat cal/g-C	Formu- lation*	Temperature		Specific Heat cal/g-C
	C	F			C	F	
MHF-7-N	-52.35	-62.23	0.7073	MHF-7-N	58.13	136.63	0.7642
MHF-7-N	-49.92	-56.88	0.7066	MHF-7-N	60.78	141.40	0.7674
MHF-7-N	-47.30	-53.14	0.7067	MHF-7-N	63.42	146.16	0.7681
MHF-7-N	-44.68	-48.42	0.7071	MHF-7-N	66.06	150.91	0.7701
MHF-7-N	-42.08	-43.74	0.7091	MHF-7-N	68.69	155.64	0.7757
MHF-7-N	-39.48	-39.06	0.7133				
MHF-7-N	-36.88	-34.38	0.7106	MHF-7-1	-49.36	-56.85	0.7199
MHF-7-N	-34.30	-29.74	0.7118	MHF-7-1	-46.68	-52.02	0.7221
MHF-7-N	-23.89	-11.00	0.7209	MHF-7-1	-44.02	-47.24	0.7216
MHF-7-N	-21.08	-5.94	0.7217	MHF-7-1	-29.25	-20.65	0.7316
MHF-7-N	-18.26	-0.87	0.7183	MHF-7-1	-26.63	-15.93	0.7321
MHF-7-N	-15.43	4.23	0.7217	MHF-7-1	-24.00	-11.20	0.7303
MHF-7-N	-12.60	9.32	0.7217	MHF-7-1	-21.38	-6.48	0.7342
MHF-7-N	-9.76	14.43	0.7241	MHF-7-1	-10.96	12.27	0.7391
MHF-7-N	-6.89	19.60	0.7267	MHF-7-1	-8.37	17.92	0.7405
MHF-7-N	-4.73	23.49	0.7248	MHF-7-1	1.59	34.86	0.7445
MHF-7-N	-1.75	28.85	0.7277	MHF-7-1	4.18	39.52	0.7473
MHF-7-N	1.21	34.18	0.7322	MHF-7-1	18.11	64.60	0.7635
MHF-7-N	4.18	39.52	0.7291	MHF-7-1	23.30	73.94	0.7601
MHF-7-N	7.14	44.85	0.7314	MHF-7-1	25.88	78.58	0.7594
MHF-7-N	10.11	50.20	0.7328	MHF-7-1	37.08	98.74	0.7717
MHF-7-N	13.06	55.51	0.7346	MHF-7-1	39.64	103.35	0.7745
MHF-7-N	16.01	60.81	0.7360	MHF-7-1	42.19	107.94	0.7763
MHF-7-N	17.05	62.69	0.7394	MHF-7-1	59.04	138.27	0.7930
MHF-7-N	20.01	68.02	0.7429	MHF-7-1	61.51	142.72	0.7945
MHF-7-N	30.31	86.56	0.7483				
MHF-7-N	32.74	90.93	0.7486	MHF-7-2	-42.96	-45.33	0.7204
MHF-7-N	35.12	95.22	0.7513	MHF-7-2	-40.14	-40.25	0.7255
MHF-7-N	37.47	99.45	0.7483	MHF-7-2	-37.33	-35.19	0.7266
MHF-7-N	42.40	107.96	0.7530	MHF-7-2	-34.52	-30.14	0.7266
MHF-7-N	44.91	112.84	0.7535	MHF-7-2	-31.70	-25.06	0.7277
MHF-7-N	47.61	117.70	0.7555	MHF-7-2	-26.40	-15.52	0.7226
MHF-7-N	50.31	122.56	0.7543	MHF-7-2	-23.57	-10.43	0.7232
MHF-7-N	53.00	127.40	0.7592	MHF-7-2	-20.76	-5.37	0.7274
MHF-7-N	55.49	131.88	0.7628	MHF-7-2	-17.94	-0.29	0.7297

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TABLE 16 (CONCLUDED)

Formulation	Temperature		Specific Heat cal/g-°C	Formulation	Temperature		Specific Heat cal/g-°C
	C	F			C	F	
MHF-7-2	-15.13	4.77	0.7350	MHF-3	-29.74	-21.53	0.7000
MHF-7-2	-12.32	9.82	0.7329	MHF-3	-25.37	-13.67	0.7000
MHF-7-2	3.12	37.62	0.7423	MHF-3	-17.82	-0.08	0.6990
MHF-7-2	5.87	42.57	0.7384	MHF-3	-15.83	3.51	0.6980
MHF-7-2	8.62	47.52	0.7443	MHF-3	-8.92	15.94	0.7040
MHF-7-2	11.35	52.43	0.7452	MHF-3	-6.95	19.49	0.7090
MHF-7-2	14.08	57.34	0.7391	MHF-3	0.32	32.58	0.7050
MHF-7-2	24.20	75.56	0.7520	MHF-3	1.85	35.33	0.7090
MHF-7-2	26.85	80.33	0.7527	MHF-3	2.30	36.14	0.7120
MHF-7-2	32.14	89.85	0.7605	MHF-3	3.83	38.89	0.7070
MHF-7-2	34.77	94.59	0.7580	MHF-3	11.46	52.06	0.7190
MHF-7-2	37.41	99.34	0.7590	MHF-3	13.41	56.14	0.7150
MHF-7-2	37.74	99.93	0.7595	MHF-3	18.98	66.16	0.7120
MHF-7-2	40.42	104.76	0.7556	MHF-3	20.96	69.73	0.7210
MHF-7-2	43.10	109.58	0.7548	MHF-3	25.43	77.77	0.7130
MHF-7-2	45.93	114.67	0.7568	MHF-3	27.36	81.25	0.7210
MHF-7-2	48.64	121.55	0.7571	MHF-3	32.64	90.75	0.7230
				MHF-3	34.58	94.22	0.7240
MHF-3*	-46.01	-50.82	0.6950	MHF-3	40.60	105.08	0.7240
MHF-3	-44.48	-48.06	0.6930	MHF-3	42.52	108.65	0.7370
MHF-3	-43.96	-47.13	0.6910	MHF-3	44.76	112.57	0.7300
MHF-3	-39.90	-39.82	0.6920	MHF-3	47.31	117.61	0.7270
MHF-3	-38.33	-36.99	0.6980				
MHF-3	-37.86	-36.15	0.7040				
MHF-3	-36.32	-33.38	0.7050				

SAMPLE COMPOSITION

Formulation	CH ₃ NH ₂ Cl, w/o	N ₂ H ₄ , w/o	H ₂ O, w/o	Other Soluble Impurities, w/o
MHF-7-N	81.3	14.2	4.2	0.3
MHF-7-1	75.9	14.5	9.3	0.3
MHF-7-2	76.2	19.1	4.4	0.3
MHF-3	84.7	14.0	1.0	0.3

*MHF-3 data from Ref. 2.

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program with the following expressions of MHF-7 specific heat (C_p) as a function of temperature (t) and composition in weight percent (w/o) N_2H_4 (H) and H_2O (W):

$$\begin{aligned}
 C_p(\text{cal/g-C}) = & 0.3335 + 2.635 \times 10^{-2} H_{(\text{w/o})} + 8.469 \times 10^{-2} W_{(\text{w/o})} \\
 & - 5.613 \times 10^{-3} H_{(\text{w/o})} W_{(\text{w/o})} + 5.87 \times 10^{-4} t(\text{C}) \\
 & - 1.56 \times 10^{-5} H_{(\text{w/o})} t(\text{C}) + 3.12 \times 10^{-5} W_{(\text{w/o})} t(\text{C}) \\
 & + 1.91 \times 10^{-6} t(\text{C})^2
 \end{aligned}$$

and

$$\begin{aligned}
 C_p(\text{Btu/lb-F}) = & 0.3237 + 2.662 \times 10^{-2} H_{(\text{w/o})} + 8.414 \times 10^{-2} W_{(\text{w/o})} \\
 & - 5.613 \times 10^{-3} H_{(\text{w/o})} W_{(\text{w/o})} + 2.881 \times 10^{-4} t(\text{F}) \\
 & - 8.64 \times 10^{-6} H_{(\text{w/o})} t(\text{F}) + 1.73 \times 10^{-5} W_{(\text{w/o})} t(\text{F}) \\
 & + 5.89 \times 10^{-7} t(\text{F})^2
 \end{aligned}$$

The standard errors of estimate for these expressions, which are represented graphically in Fig. G-4 and G-4a of Appendix G for the nominal formulation, are 3.11×10^{-3} cal/g-C (Btu/lb-F).

(U) Viscosity Measurements

- (U) Viscosity measurements were conducted on Florox, MOR-5, and MHF-7. An all-metal capillary viscometer, developed during the previous programs (Ref. 1 and 2) under Contracts AF04(611)-10546 and AF04(611)-11407, was used for the measurements on Florox and MOR-5, while pyrex Cannon-Ubbelohde and Zhukov viscometers were used for the MHF-7 measurements.
- (U) The design of the all-metal apparatus is shown schematically in Fig. 12. In this apparatus, the viscosity is obtained by observing the flowrate through the capillary tubing and the corresponding driving fluid head, which in this apparatus is a simple gravity head resulting from a difference in the elevation of the liquid level in the two legs of the U-tube. The reservoir in one of these legs is a section of 0.75-inch tubing which contains a magnetic float at the gas-liquid interface. The position

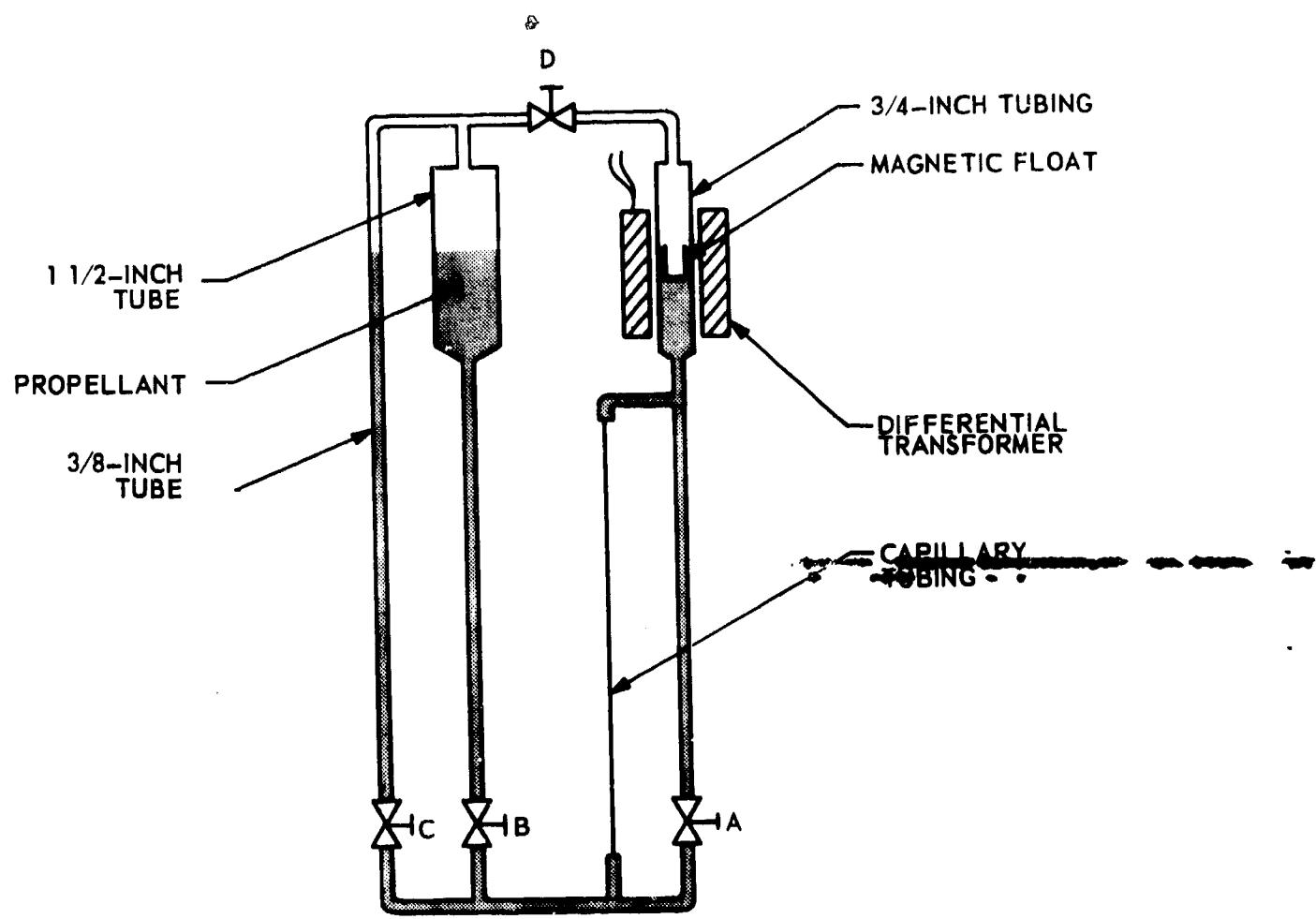


Figure 12. Capillary Viscometer Schematic

of this float within a vertical range of approximately 6 inches is sensed by a differential transformer unit surrounding the tubing. For the other leg of the U-tube, valves B and C provide a choice between a 1-1/2-inch and 3/8-inch tubing reservoir.

(U) The viscometer is constructed entirely of stainless-steel tubing and fittings to permit testing of corrosive liquids at pressures up to 1000 psi. The capillary tubing is 0.023-inch ID and approximately 26-1/2 inches long. This long, large-bore capillary was selected in an attempt to minimize the relative importance of entrance and exit friction losses at low kinematic viscosities, which may approach 0.1 centistoke for propellants of interest. For the case of flow between the 3/4-inch float reservoir and the 1-1/2-inch reservoir, this capillary would lead to experimental flow times ranging from minutes to hours in the viscosity range contemplated. To increase the speed of the test process at the higher viscosities, the option of the 3/8-inch reservoir has been provided, which permits setting up a much larger differential head within the operating range of the transducer and float. In addition, this option permits testing of a given viscosity under significantly different driving heads, flow velocities, and hence, Reynolds numbers, for the capillary. This feature could permit estimation or calibration of the end effects at low viscosities. It may be possible to extend the applicability of the viscometer into a range where end effects are important through a technique of self-calibration, in which a given viscosity is measured over a sufficiently wide Reynolds number range.

(U) Not shown in the figure are accessory connections and valving for loading, venting, and/or pressurizing the viscometer with inert gas. The overall unit, approximately 5 feet tall, is housed in a temperature-controlled dry box equipped with heater, circulation fans, thermocouples, pressure transducer, etc.

(U) In operation, the viscometer is filled with liquid propellant to an elevation within the sensing range of the float and transformer. A differential head is established between the float reservoir and one of the other reservoirs by inert gas pressurization or by venting propellant vapors from one of the reservoirs. Subsequently, this head is allowed to dissipate by flow through the capillary tubing. A line and valve (D) connecting the gas spaces of the float reservoir and the other reservoirs separate these spaces while establishing the initial liquid head, and permit equalization of the pressure over the liquid during the capillary flow process. The flow through the capillary may be in either direction; the choice of flow direction determines the elevation of initial fill, or equilibrium liquid level position, within the range of the float and transformer.

(U) Calibration of the relative volumetric capacities of the U-tube legs establishes differential liquid heads as a function of float position with reference to the equilibrium position. Valve A allows bypassing the capillary tubing to facilitate the processes of establishing a differential head and the equilibrium position. Viscosity is determined from the time history of head dissipation in flow through the capillary plus calibration of its flow resistance.

(U) The flow process leads nominally to an exponential decay of liquid head with time which may be given as

$$\frac{d}{dt} (\ln x) = \frac{C}{\nu}$$

where x is float displacement from the equilibrium position, t is time, ν is the kinematic viscosity of the liquid, and C is a nominally con-

stant factor involving fundamental constants and instrument parameters (capillary length and radius, and areas of the U-tube reservoir arms).

- (U) The principal calibration factor, C, was obtained from tests with a liquid of known kinematic viscosity (e.g., deionized water). Several tests were conducted at each viscosity level using each of the optional secondary reservoirs which complete the U-tube with the float reservoir. Values derived for the principal calibration factors (C corresponding to each optional secondary arm) were consistent within 3 percent, and agree reasonably well with estimates based on dimensions of the apparatus. The scatter in experimental values was largely caused by uncertainty or variation in the temperature, and hence the viscosity, for a run. Temperature has negligible direct effect on the instrument parameters.
- (U) The principal difficulty experienced in operating the viscometer was sinking of the sensor float during the processes of bringing the system to test temperature and establishing the initial fluid head for a run. Experimental procedures were developed to overcome this difficulty. In previous measurements (Ref. 2), the sensor float tended to hang up in its tubing reservoir and would not follow the flow of liquid. A mechanical vibrator was adapted to the system to correct this behavior. Many tests had been conducted (Ref. 2) to ascertain that, with proper operating procedure, the vibrator itself does not introduce observable error in the viscosity.
- (U) In viscosity determinations on MHF-7, standard Cannon-Ubbelohde and modified Ostwald (Zhukov) capillary viscometers, fabricated from pyrex, were employed. The Cannon-Ubbelohde viscometer, which was adapted for the measurements by the installation of flow directing and sealing valves,

was used for measurements over the temperature range of -65 to 32 F (-53.9 to 0 C). Viscosity measurements at room temperature and above were conducted with the Zhukov viscometer, which is more suited to the higher pressures.

(U) From the equation

$$\eta = (hg \rho r^4 t \pi / 8 \ell v) - (m \rho v / 8 \ell \pi t)$$

where

h = liquid head, centimeters
 g = gravitational constant, cm-sec^2
 ρ = density, gm/cc
 r = capillary radius, centimeters
 t = time of flow, seconds
 v = volume of flow, cc
 ℓ = capillary length, centimeters
 m = complex constant (in general, this can be assumed as unity with no appreciable error)

the equation

$$\eta = C \rho t - B \rho / t$$

where

C = viscometer constant
 B = assumed constant

can be derived. The second term ($B \rho / t$) in this equation becomes zero as the capillary-end kinetic energy corrections become insignificant

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(i.e., when t is large). The viscometer constant C was evaluated from the measured times of liquid flow through the capillary for two or more liquids of known viscosities. The Cannon-Ubbelohde apparatus had a certified calibration of 0.00790 centistokes (cs)/sec for C , while a viscometer constant of 0.00757 cs/sec was determined for the Zhukov apparatus by calibrations with distilled and degassed water and Cannon viscosity standard fluid No. 0.1 S-6-57-2c.

(c) Viscosity of Florox. The kinematic viscosity of liquid Florox (ClF_3^0) was measured over the range 38.5 to 203.4 F (3.6 to 95.2 C) using the float-level-indicating, stainless steel, capillary tube viscometer. The tendency for the float to bind or stick to the wall (even with use of the vibrator) during initial runs was eliminated by reversing the normal flow path to allow the float to rise with increasing liquid level rather than fall with decreasing liquid level. Three runs were made at each of five temperature levels with one sample of propellant (which was loaded into the apparatus by means of a vacuum line); duplicate measurements were made with a second sample of propellant over four temperature levels. Results of these runs are shown in Table 17 with the chemical analyses of the samples. These kinematic viscosity data were correlated with the ClF_3^0 density data by a least squares computer curve-fit program to give the following expressions of ClF_3^0 absolute viscosity as a function of temperature:

$$\log \eta_{(\text{cp})} = -1.9567 + \frac{521.12}{T(\text{K})}$$

and

$$\log \eta_{(\text{lb}/\text{ft sec})} = -5.1293 + \frac{938.01}{T(\text{R})}$$

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TABLE 17

VISCOSITY DATA ON SATURATED LIQUID FLOROX*

Sample No. 1			Sample No. 2		
Temperature		Kinematic (Measured), CS	Temperature		Absolute (Calculated), CP
F	C		F	C	
39.5	4.2	0.449	79.8	26.6	0.588
38.8	3.8	0.465	80.1	26.7	0.589
38.5	3.6	0.458	80.4	26.9	0.595
73.4	23.0	0.339	118.8	48.2	0.452
73.4	23.0	0.336	118.8	48.2	0.457
74.1	23.4	0.333	118.8	48.2	0.455
117.7	47.6	0.255	157.1	69.5	0.359
118.1	47.8	0.258	157.1	69.5	0.371
118.1	47.8	0.261	157.5	69.7	0.371
157.1	69.5	0.213	157.9	69.9	0.373
157.1	69.5	0.212	203.4	95.2	0.292
157.1	69.5	0.210	203.4	95.2	0.292
201.7	94.3	0.179	203.4	95.2	0.287
201.4	94.1	0.179	0.293	0.176	
201.1	93.9	0.180	0.295		

*Sample Compositions:

Sample 1	Sample 2
98.5	97.9
0.3	1.3
0.4	0.4
0.1	-
0.4	0.1
0.1	0.1
0.3	0.2

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The standard errors of estimate of these expressions, which are represented graphically in Fig. E-5 and E-5a of Appendix E, are 2.1% in η .

(c) Viscosity of MOR-5. The kinematic viscosity of MOR-5 (nominal composition: 78 w/o ClF_3^0 - 22 w/o ClF_5) was measured over the temperature range of 79.1 to 197.7 F (26.2 to 92.1 C) using the float-level-indicating, stainless steel, capillary tube viscometer. After the apparatus was loaded using a vacuum line, three or more runs were made at each of four temperature levels with one sample of propellant. Because the oxidizer is a mixture of two components having widely different boiling points, duplicate measurements were made at ambient temperature (~ 80 F) at the beginning and end of the series of measurements. This was done to determine any significant change in the viscosity resulting from possible changes in the sample composition due to the various sample transfer operations (e.g., venting of the ullage gases) required in the measurements. Table 18 contains the results of these measurements and the chemical analyses of the sample. These results show that the ambient temperature measurements made at the end of the series of runs resulted in values $\sim 1\frac{1}{2}$ -percent greater than those made at the beginning of the series; this indicates a possible change in viscosity of the mixture because of ClF_3^0 enrichment due to the loss of some of the lower boiling ClF_5 during venting.

(c) All of the data were correlated by a least squares computer program with the following expressions:

$$\log \eta_{(\text{cp})} = -1.8177 + \frac{458.69}{T(\text{K})}$$

and

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TABLE 18
VISCOSITY DATA ON SATURATED LIQUID MOR-5*

Temperature		Kinematic (Measured), cs	Absolute (Calculated), cp
F	C		
79.1	26.2	0.283	0.519
79.1	26.2	0.284	0.521
79.1	26.2	0.285	0.522
119.5	48.6	0.230	0.405
119.5	48.6	0.221	0.390
118.8	48.2	0.223	0.394
118.8	48.2	0.228	0.403
118.8	48.2	0.229	0.404
119.1	48.4	0.227	0.401
157.5	69.7	0.195	0.330
157.5	69.7	0.194	0.328
157.1	69.5	0.197	0.333
197.0	91.7	0.171	0.275
197.7	92.1	0.174	0.279
197.7	92.1	0.174	0.279
197.7	92.1	0.173	0.278
80.1	26.7	0.282	0.516
80.5	26.9	0.286	0.524
79.4	26.3	0.292	0.535

*Sample Composition:

ClF ₃ 0, w/o	77.5
ClF ₅ , w/o	21.7
ClF ₃ , w/o	0.6
FC10 ₂ , w/o	0.2

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$$\log \eta_{(lb/ft \ sec)} = -4.9903 + \frac{825.65}{T(R)}$$

The standard errors of estimate of these equations, which are represented graphically in Fig. F-5 and F-5a of Appendix F, are 1.9% in η .

(U) Viscosity of MHF-7. Experimental viscosity measurements were conducted on 6 selected MHF-7 formulations (described in the "Propellant Formulation and Chemical Analyses" section as formulations -N, -1, -2, -3, -4, and -5) over the temperature range of -65.1 to 175.0 F (-53.9 to 79.4 C) using the Cannon-Ubbelohde and Zhukov capillary viscometers. The resulting kinematic viscosity data (shown in Table 19 with the corresponding chemical analyses of the formulations) were correlated as a function of temperature and composition with previously determined (Ref. 6) data on MHF-3 (shown in Table 20) through the use of a least squares curve-fit computer program. The correlation, which represents a ± 5 w/o variation of each of the formulation components from a nominal MHF-7 formulation (81 w/o $\text{CH}_3\text{N}_2\text{H}_3$ - 14 w/o N_2H_4 - 5 w/o H_2O), also included the conversion (by use of the density equation) to absolute viscosity and is represented by the following expressions:

$$\begin{aligned} \log \eta_{(cp)} &= -4.9085 + \frac{3614.4}{T(K)} - \frac{1.07370 \times 10^6}{T(K)^2} \\ &+ \frac{1.26262 \times 10^8}{T(K)^3} + 0.10612 W_{(w/o)} - 3.540 \times 10^{-2} H_{(w/o)} \\ &- \frac{76.579 W_{(w/o)}}{T(K)} + \frac{22.601 H_{(w/o)}}{T(K)} + \frac{15264.6 W_{(w/o)}}{T(K)^2} \\ &- \frac{3551.7 H_{(w/o)}}{T(K)^2} \end{aligned}$$

and

TABLE 19
VISCOSITY DATA ON LIQUID MHF-7 FORMULATIONS

Formulation	Temperature		Kinematic (Measured), cs	Absolute (Calculated), cp
	F	C		
MHF-7-N	- 65.1	- 53.9	30.02	29.21
MHF-7-N	- 35.0	- 37.2	8.872	8.498
MHF-7-N	32.0	0.0	2.050	1.893
MHF-7-N	77.0	25.0	1.137	1.024
MHF-7-N	100.0	37.8	0.906	0.805
MHF-7-N	138.2	59.0	0.662	0.575
MHF-7-N	175.0	-	0.519	0.441
MHF-7-1	- 60.0	- 51.1	52.56	51.77
MHF-7-1	- 35.0	- 37.2	16.23	15.78
MHF-7-1	- 5.9	- 21.1	6.406	6.134
MHF-7-1	32.0	0.0	2.742	2.572
MHF-7-1	77.0	25.0	1.401	1.282
MHF-7-1	100.0	37.8	1.080	0.975
MHF-7-1	138.2	59.0	0.762	0.673
MHF-7-1	175.0	79.4	0.578	0.499
MHF-7-2	- 50.1	- 45.6	13.79	13.41
MHF-7-2	- 30.0	- 34.4	7.031	6.763
MHF-7-2	- 5.8	- 21.0	3.799	3.608
MHF-7-2	32.0	0.0	1.926	1.792
MHF-7-2	77.0	25.0	1.101	0.999
MHF-7-2	100.0	37.8	0.880	0.788
MHF-7-2	138.2	59.0	0.650	0.569
MHF-7-2	175.0	79.4	0.509	0.436
MHF-7-3	- 64.8	- 53.8	77.60	76.11
MHF-7-3	- 45.8	- 43.2	27.74	26.94
MHF-7-3	- 30.1	- 34.5	15.39	14.82
MHF-7-3	- 5.8	- 21.0	6.557	6.235
MHF-7-3	32.0	0.0	2.803	2.611
MHF-7-3	77.0	25.0	1.399	1.271
MHF-7-3	100.0	37.8	1.073	0.962
MHF-7-3	138.2	59.0	0.752	0.659
MHF-7-3	175.0	79.4	0.573	0.491

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(CONCLUDED)

Formulation	Temperature		Kinematic (Measured), cs	Absolute (Calculated), cp
	F	C		
MHF-7-4	- 65.1	- 53.9	29.72	28.73
MHF-7-4	- 34.8	- 37.1	8.816	8.387
MHF-7-4	- 5.7	- 20.9	3.962	3.711
MHF-7-4	32.0	0.0	1.961	1.799
MHF-7-4	77.0	25.0	1.087	0.972
MHF-7-4	100.0	37.8	0.867	0.765
MHF-7-4	138.2	59.0	0.636	0.548
MHF-7-4	175.0	79.4	0.501	0.422
MHF-7-5	- 44.0	- 42.2	6.657	6.372
MHF-7-5	- 25.0	- 31.7	4.037	3.825
MHF-7-5	- 6.0	- 21.1	2.708	2.540
MHF-7-5	32.0	0.0	1.484	1.363
MHF-7-5	77.0	25.0	0.898	0.804
MHF-7-5	100.0	37.8	0.739	0.653
MHF-7-5	138.2	59.0	0.564	0.487
MHF-7-5	175.0	79.4	0.456	0.385

SAMPLE COMPOSITION

Formulation	CH ₃ N ₂ H ₃ , w/o	N ₂ H ₄ , w/o	H ₂ O, w/o	Other Soluble Impurities, w/o
MHF-7-N	81.3	14.2	4.2	0.3
MHF-7-1	75.9	14.5	9.3	0.3
MHF-7-2	76.2	19.1	4.4	0.3
MHF-7-3	81.2	8.8	9.5	0.5
MHF-7-4	86.5	8.9	4.3	0.3
MHF-7-5	80.7	18.7	0.3	0.3

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TABLE 20

EXPERIMENTAL SATURATED LIQUID VISCOSITY
DATA FOR MHF-3 (Ref. 6)

Formulation	Temperature, F	Viscosity, centistokes
MHF-3	195.1	0.42
MHF-3	165.0	0.49
MHF-3	100.0	0.76
MHF-3	92.1	0.80
MHF-3	83.7	0.86
MHF-3	77.0	0.92
MHF-3	32.0	1.50
MHF-3	- 4.0	2.70
MHF-3	- 40.0	6.30
MHF-3A	201.0	0.42
MHF-3A	168.0	0.50
MHF-3A	125.0	0.64
MHF-3A	74.4	0.97
MHF-3A	32.2	1.56
MHF-3A	- 30.8	4.88
MHF-3A	- 68.3	18.3
MHF-3W	202.0	0.42
MHF-3W	158.0	0.53
MHF-3W	104.5	0.76
MHF-3W	81.4	0.94
MHF-3W	32.0	1.65
MHF-3W	- 3.6	2.99
MHF-3W	- 37.8	7.03
MHF-3W	- 68.6	23.1
MHF-3AM	200.0	0.43
MHF-3AM	141.2	0.58
MHF-3AM	118.6	0.67
MHF-3AM	78.0	0.94
MHF-3AM	32.2	1.60
MHF-3AM	- 32.6	5.77
MHF-3AM	- 70.8	24.4

SAMPLE COMPOSITION

Mixture	CH ₃ NH ₂ , w/o	N ₂ H ₄ , w/o	H ₂ O, w/o	Other Soluble Impurities, w/o
MHF-3	85.6	13.9	0.3	0.2
MHF-3A	87.3	12.2	0.4	0.1
MHF-3W	85.1	12.8	1.7	0.4
MHF-3AM	89.0	9.4	1.2	0.4

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$$\begin{aligned}
 \log \eta_{(lb/ft \ sec)} = & -8.0809 + \frac{6505.63}{T(R)} - \frac{3.47864 \times 10^6}{T(R)^2} \\
 & + \frac{7.36338 \times 10^8}{T(R)^3} + 0.10612 W_{(w/o)} - 3.540 \times 10^{-2} H_{(w/o)} \\
 & - \frac{137.843 W_{(w/o)}}{T(R)} + \frac{40.683 H_{(w/o)}}{T(R)} + \frac{49457.5 W_{(w/o)}}{T(R)^2} \\
 & - \frac{11507.8 H_{(w/o)}}{T(R)^2}
 \end{aligned}$$

where

η = absolute viscosity in centipoises (cp) or (lb/ft sec)

T = absolute temperature in K or R

$H_{(w/o)} = N_2H_4$ content in weight percent

$W_{(w/o)} = H_2O$ content in weight percent

The standards errors of estimate of these expressions are 2.4% in η . Graphical representations of the nominal MHF-7 mixture as described by these expressions are shown in Fig. G-5 and G-5a, respectively, of Appendix G.

Thermal Conductivity Measurements

(U) In an attempt to expand preliminary data obtained previously under Contract AF04(611)-11407 (Ref. 2), thermal conductivity measurements were conducted on ClF_5 in a steady-state, concentric-cylinder conductivity cell. Experimental difficulties in use of the steady-state cell with highly reactive oxidizers prompted the in-house development of a transient technique, which was subsequently used under this program to determine the thermal conductivities of ClF_5 , ClF_3 , Florox, M0R-5, and MHF-7.

(U) The steady-state apparatus (pictorially represented in Fig. 13) was used successfully in previous efforts to measure thermal conductivities of $50\text{ N}_2\text{H}_4$ -50 UDMH (Ref. 1), $\text{CH}_3\text{N}_2\text{H}_3$ (Ref. 1), $(\text{CH}_3)_2\text{N}_2\text{H}_2$ (Ref. 2), MHF-3 (Ref. 2), and MHF-5 (Ref. 2). In this apparatus, the test fluid is contained in a thin annular passage between two aluminum alloy cylinders. The annulus is approximately 1 inch in diameter, 0.020 inch thick, and 5-3/4 inches long. The ends of the annulus are sealed with two Teflon O-rings, which hold the cylinders concentrically and minimize the heat conduction path between the cylinders. To maintain end effects at a minimum, two thermal barriers fabricated of Teflon are fitted over the ends of the cylinders.

(U) The cell is held together by two stainless-steel end plates which fit over the thermal barriers. Six pairs of copper-constantan thermocouples are embedded at various positions in both cylinders, close to the surface of the cavity containing the test fluid. Thermocouple wire diameter is maintained as small as possible to minimize heat losses. An electrical resistance heater, located in the inner cylinder, supplies the heat energy to establish a temperature gradient across the liquid layer. The temperature of the outer cylinder is regulated by immersion of the cell in a constant-temperature bath.

(U) The experimental procedure is straightforward but tedious and time consuming. The test fluid is placed into a stainless-steel loading manifold attached to the cell. By proper manipulation of the loading manifold valves the annulus is first evacuated, and then the test fluid is vacuum transferred into the cell. The cell is placed in the constant-temperature bath which is adjusted to some preselected and regulated temperature. Electrical power is applied to the cell heater through

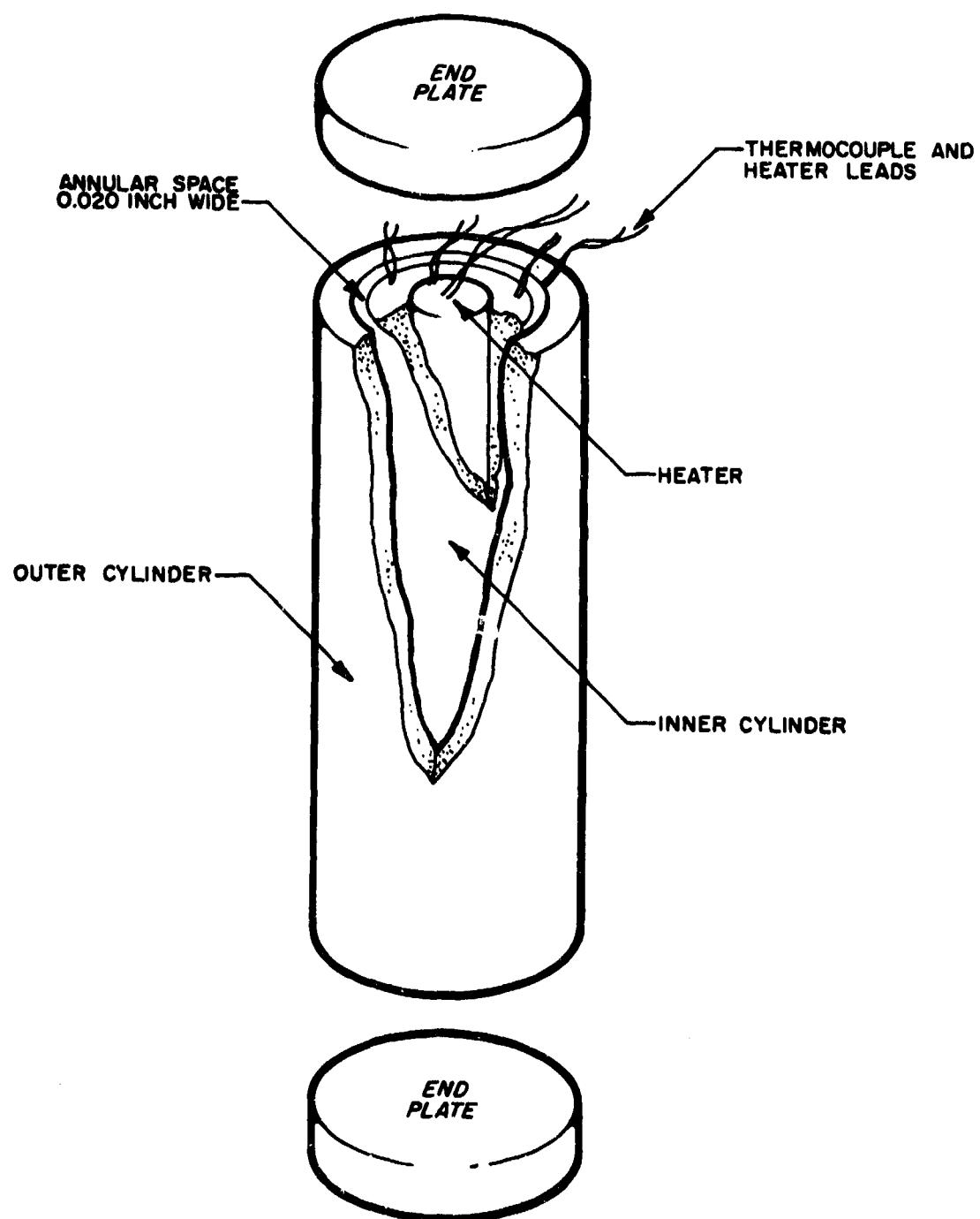


Figure 13. Steady-State Thermal Conductivity Cell

use of a regulated d-c power supply until a temperature gradient of the desired magnitude is obtained across the annulus (liquid layer). Temperature gradients are maintained at approximately 1 F to minimize convection. After thermal equilibrium is attained, measurements of heater voltage and current are made through use of a Leeds and Northrup K-3 potentiometer in conjunction with a precision volt box and current shunt. This instrument is also used to measure the temperature gradient across the annulus and the bath temperature.

(U) The thermal conductivity of the test fluid is calculated through use of the equation:

$$k = \frac{Q \Delta X}{A \Delta T}$$

where

k = thermal conductivity, Btu/hr-ft-F
 Q = heat flux, Btu/hr
 A = heat transfer area normal to heat flux, sq ft
 ΔX = liquid layer thickness, feet
 ΔT = temperature gradient, F

(U) Prior to conducting actual thermal conductivity measurements on test fluids, a series of vacuum calibrations of the cell are made. These calibrations are necessary to account for cell heat losses along thermocouple wires, along heater lead wires, and through the ends of the cylinders. Calibrations are made at appropriate intervals throughout the temperature range of interest. Electrical power levels required to maintain given temperature gradients (~ 1 F) across the annulus are measured at each operating temperature. These heat losses are subtracted from the total heat input measured during actual thermal conductivity runs to obtain a net heat input.

(U) The concentric cylinder conductivity cell, which is typical of the various steady-state measurement techniques for liquid thermal conductivity, requires a relatively long measurement period for the establishment of equilibrium temperatures in the liquid as well as a restrictive experimental procedure to eliminate errors resulting from convection and boundary (end) effects. These factors, besides being a general source of inaccuracy and inefficiency in the thermal conductivity determinations, proved to be a major obstacle in measurements on highly reactive or thermally sensitive fluids. As a result, Rocketdyne conducted an in-house program on the development of a more suitable technique for the measurement of liquid thermal conductivity. This in-house program provided an acceptable transient method which eliminates many of sources of error of the steady-state methods and requires only a relatively short measurement time.

(U) The basis of the transient measurement technique (Ref. 14 and 15) is a closed form solution of the time-dependent heat conductivity problem which can be obtained for the case of a continuous line source in an infinite medium. The resulting equation shows that as a thin wire immersed in a fluid is heated from time zero, the temperature of the wire increases proportionally to the logarithm of time, with the constant of proportionality involving only the heat supplied and the thermal conductivity of the fluid. Therefore, if the temperature rise of the wire as a function of time and the electrical heat supplied are measured, the thermal conductivity can be calculated by:

$$k = \frac{Q}{4\pi} \left(\frac{\Delta \ln t}{\Delta T} \right)$$

where

k = thermal conductivity
 Q = heat supplied
 t = time
 T = temperature of wire

(U) Although this "hot-wire" technique has been employed in the past by several investigators (Ref. 14 and 15), a unique feature of the transient-state thermal conductivity apparatus developed at Rocketdyne is that the conductivity cell is an all-metal assembly (with the exception of a Teflon seal on the electrical lead-throughs) as opposed to the glass cells usually employed. The all-metal fabrication enables measurements to be made on a number of materials which are of questionable compatibility with glass (such as fluorinated oxidizers), at high pressures (over 1000 psi), and at elevated temperatures (on saturated liquids with high vapor pressures). The body of the cell used for measurements on the oxidizers (Fig. 14) is fabricated from 321 stainless steel, while a second apparatus (similar in design with slightly different cell dimensions) fabricated from aluminum (Ref. 13) was used for measurements on MHF-7. The electrical leads through the ends of the cell utilize Conax thermocouple glands with Teflon seals. The central (active) portion of the measurement wire is a 0.003-inch-diameter platinum wire approximately 20-cm long with 0.020-inch-diameter platinum leads out of the sample container. Because the measurement wire has a very large length-to-diameter ratio, the end effects from conduction to the leadout wires provides a negligible contribution to the total heat flow from the wire.

(U) The 0.003-inch-diameter platinum wire was utilized as both a heat source and temperature-sensing element. The wire was connected as one arm of a Wheatstone bridge with the other arms made up of precision decade resistance boxes as shown in Fig. 14. To provide stability and low noise, a lead acid storage battery was used as the voltage source. The temperature change of the wire was measured by recording the unbalance voltage of the bridge on a strip chart recorder as the resistance of the platinum wire changed with its temperature rise. The recorder was set to provide a record over the desired portion of full scale using the varia-

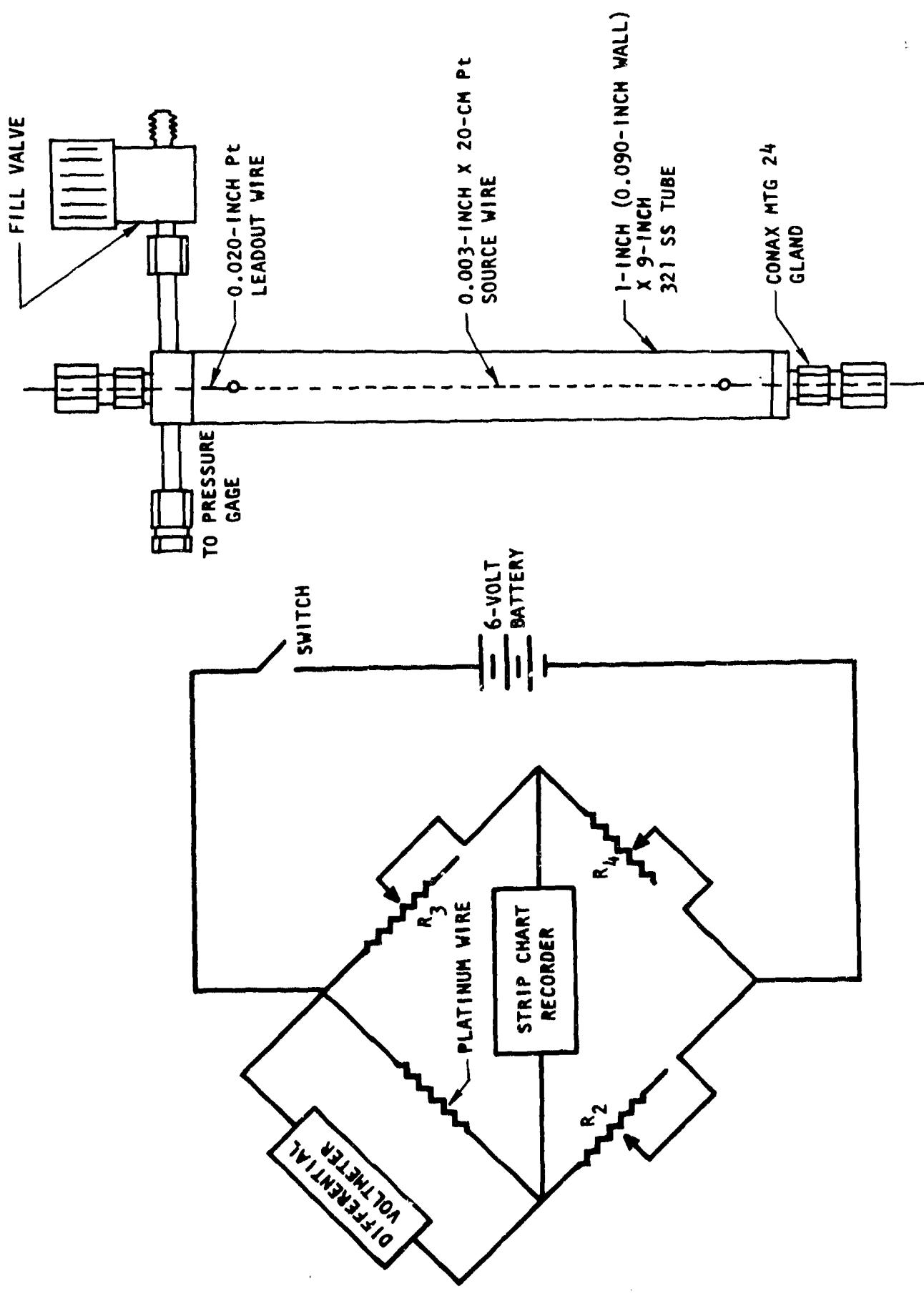


Figure 14. "Hot-Wire" Thermal Conductivity Apparatus

ble gain feature of the recorder employed. Direct correlation of recorded deflection to resistance change was made for each run by setting a resistance increment in R_4 and observing the recorder deflection; this increment was directly related (by the arm ratios) to the resistance change in R_1 , the platinum measuring wire. The heat supplied to the wire was determined from its resistance (obtained from the ratio of the decade resistance boxes and the voltage drop across the wire) measured with a precision differential voltmeter.

(U) The entire cell was immersed in a constant-temperature bath which was adjusted to the temperature at which measurements were made. At each temperature, approximately 12 to 16 time-voltage records were obtained using three to four different power inputs. The time vs voltage trace obtained on the strip chart recorder was converted to a time vs temperature plot on semilog coordinate paper. A nonlinearity in this plot for times less than a few tenths of a second was caused by the finite heat capacity of the heating wire and by the slow response time of the recorder pen. The onset of free convection (which is one of the major error sources in equilibrium methods) was clearly indicated by the deviation of the plot from a straight line. The slope of this curve, which gives $\Delta \ln t / \Delta T$, was obtained using only the straight line portion of the curve. Values of the thermal conductivity were obtained for each of the runs made at various preselected temperature levels and the values reported at a given temperature level were an average of approximately 12 separate time-voltage runs on the recorder. The sum of the instrumental errors (e.g., voltmeter decade resistance boxes and dimension measurement of wire) was estimated as 0.3 percent.

(U) Thermal Conductivity of ClF₅. Under this program, additional thermal conductivity measurements were conducted on propellant-grade (assay > 99.0 w/o) ClF₅ at 20, 40, and 80 C using the concentric cylinder steady-state thermal conductivity cell. Initial conductivity measurements were made at 20 C (68 F) using four different temperature gradients (ranging from 0.331 to 1.057 F) across the cell annulus. The thermal conductivity values obtained ranged from 4.58×10^{-2} to 4.92×10^{-2} Btu/hr-ft-F, with an average value of 4.72×10^{-2} Btu/hr-ft-F. This value is considerably lower than the 6.08×10^{-2} Btu/hr-ft-F obtained in previous measurements (using the same apparatus) under Contract AF04(611)-11407 (Ref. 2). During subsequent measurements at 40 C (104 F), the data varied from 3.13×10^{-2} to 4.0×10^{-2} Btu/hr-ft-F; a general downward drift in conductivity was noted from measurement to measurement. At this point, the ClF₅ sample in the cell was replaced with a fresh supply of liquid.

(U) Measurements of 40 C (104 F) were repeated with the new sample of liquid, but again erratic results were obtained with the values ranging from 2.76×10^{-2} to 4.00×10^{-2} Btu/hr-ft-F. Using the same liquid charge in the cell, four measurements were made at 80 C (176 F); these data ranged from 3.68×10^{-2} to 4.40×10^{-2} Btu/hr-ft-F, with each succeeding experimental value being higher than the preceding one.

(U) In an attempt to resolve these apparent anomalies, the ClF₅ was removed from the cell and the cell operation was checked out with a low vapor pressure liquid (FC-75) and a high vapor pressure liquid (Freon 113). Several measurements were made on FC-75 at 20 C (68 F) and 80 C (176 F). The values obtained were lower than the published values; also the slope of the measured values did not agree with the published curve. A single measurement made with Freon 113 was found to be about 10 percent lower than the published value. Although the data from these measurements did

not agree exactly with the published values, the precision was good and no drifting or other anomalous behavior was noted. After careful consideration of all the factors involved, the presence of gas bubbles in the cell during the ClF_5 measurements was thought to be the most likely source of trouble.

(U) A final attempt was made to obtain reproducible data at 40 C using carefully degassed ClF_5 . Loading of the cell was accomplished by a combination of pressurization, gravity flow, and condensation. The thermal conductivity values that were obtained varied from 5.57×10^{-2} to 6.38×10^{-2} Btu/hr-ft-F. This was a large increase in the average of the thermal conductivity values obtained, but there was no significant improvement in reproducibility. Because of the large scatter in the data, the thermal conductivity values obtained were not considered valid. In view of the development and successful utilization of the "hot-wire" thermal conductivity technique, it was decided to abandon further attempts to measure ClF_5 thermal conductivity with the steady-state concentric cylinder apparatus.

(U) Thermal conductivity measurements were then conducted on saturated liquid ClF_5 using the "hot-wire" apparatus. The measurements, which covered the temperature range of -31.7 to 130.2 F (-35.4 to 54.6 C), were hindered in the upper temperature regions by the immediate onset of free convection in the ClF_5 and apparent reaction of the oxidizer with the platinum wire. The experimental data, shown in Table 21, with the sample composition, were curve-fitted by a least-squares computer program with the following expressions:

TABLE 21

THERMAL CONDUCTIVITY DATA ON SATURATED LIQUID ClF_5^*

Temperature		Experimental Thermal Conductivity, Btu/hr-ft-F	Calculated** Thermal Conductivity	
F	C		Btu/hr-ft-F	cal/cm-sec-C $\times 10^4$
-31.7	-35.4	0.0867	0.0834	3.45
-12.6	-24.8	0.0873	0.0860	3.55
-12.6	-24.8	0.0884	0.0860	3.55
6.7	-14.1	0.0879	0.0886	3.66
6.7	-14.1	0.0879	0.0886	3.66
26.5	-3.1	0.0954	0.0912	3.77
26.5	-3.1	0.0907	0.0912	3.77
26.5	-3.1	0.0994	0.0912	3.77
42.0	5.6	0.0807	0.0933	3.86
42.0	5.6	0.0911	0.0933	3.86
42.0	5.6	0.0836	0.0933	3.86
55.4	13.0	0.0884	0.0951	3.93
55.4	13.0	0.0884	0.0951	3.93
70.0	21.1	0.0988	0.0971	4.01
70.0	21.1	0.1023	0.0971	4.01
86.0	30.0	0.1000	0.0993	4.10
86.0	30.0	0.1012	0.0993	4.10
100.2	37.9	0.1335	0.1012	4.18
100.2	37.9	0.1046	0.1012	4.18
115.2	46.2	0.0827	0.1032	4.27
115.2	46.2	0.0855	0.1032	4.27
130.2	54.6	0.1185	0.1052	4.35

*Sample Composition:

ClF_5 , w/o 99.9
 HF, w/o 0.1
 ClF_3 trace

**From curve-fit of experimental data.

$$k_{(Btu/hr-ft-F)} = 8.766 \times 10^{-2} + 1.35 \times 10^{-4} t_{(F)}$$

and

$$k_{(cal/cm-sec-C)} = 3.803 \times 10^{-4} + 1.00 \times 10^{-6} t_{(C)}$$

The standard errors of estimate for these equations were 1.108×10^{-2} Btu/hr-ft-F and 4.580×10^{-5} cal/cm-sec-C, respectively. The expression in the English units is represented graphically in Fig. 15. The unusually large data scatter in the "hot-wire" thermal conductivity measurements on ClF_5 was due largely to the very early onset of free convection in ClF_5 and a consequent short measurement period.

(U) Thermal Conductivity of ClF_3 . Thermal conductivity measurements were conducted on ClF_3 over the temperature range of -29.1 to 185.6 F (-33.9 to 85.3 C) using the "hot-wire" cell. Two sets of measurements were conducted on two ClF_3 samples using two different platinum wires in the stainless steel cell. The resulting data, shown in Table 22 with the sample compositions, were curve-fitted by a least-squares computer program with the following expressions:

$$k_{(Btu/hr-ft-F)} = 0.118 - 1.2 \times 10^{-4} t_{(F)}$$

and

$$k_{(cal/cm-sec-C)} = 4.74 \times 10^{-4} - 8.7 \times 10^{-7} t_{(C)}$$

The standard errors of estimate of these expressions are 1.86×10^{-3} Btu/hr-ft-F and 7.71×10^{-6} cal/cm-sec-C, respectively. A graphical representation of the expression in English units is given in Fig. 16.

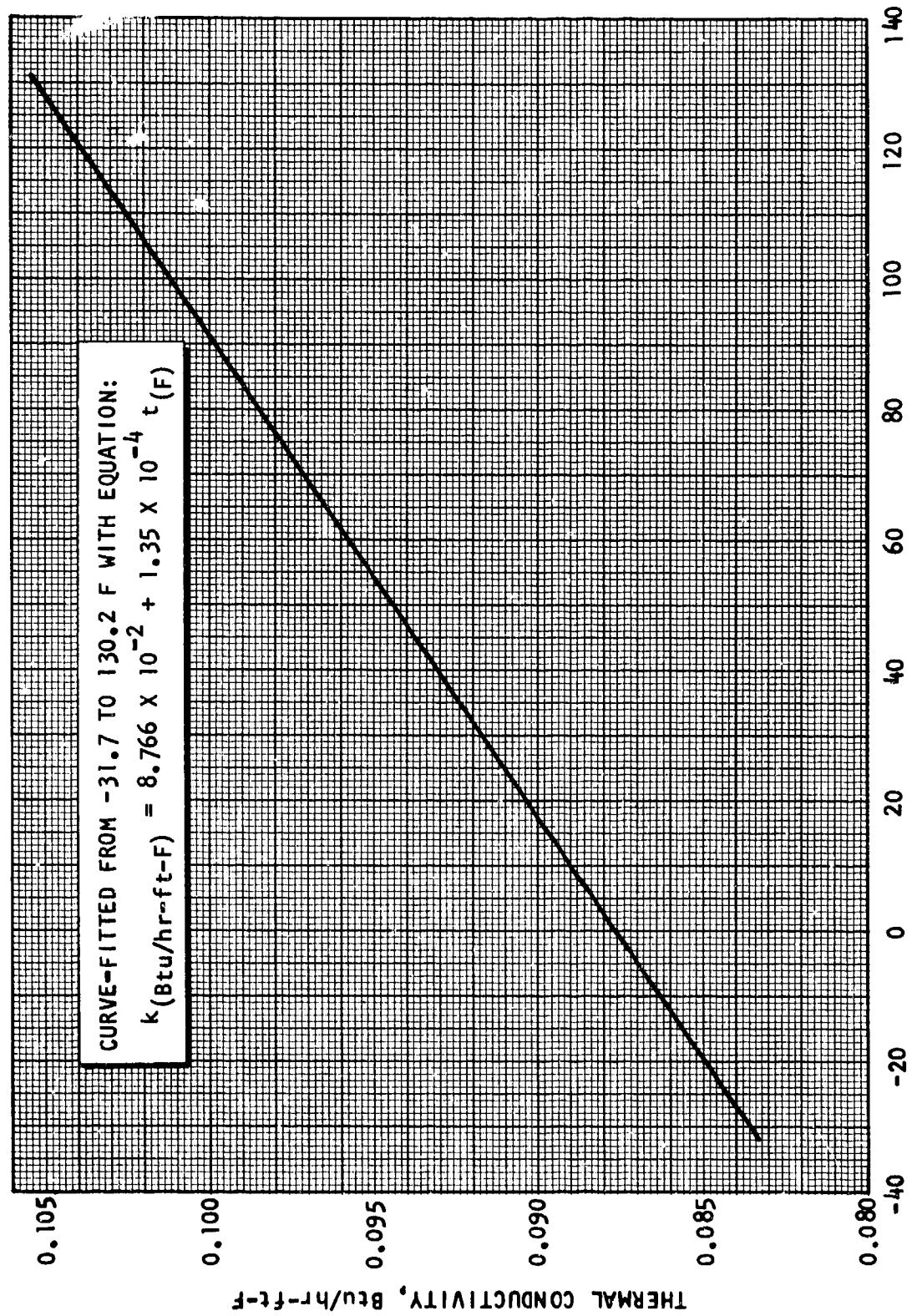


Figure 15. Thermal Conductivity of Saturated Liquid ClF_5

TABLE 22

THERMAL CONDUCTIVITY DATA ON SATURATED LIQUID ClF_3^*

Measurement** Series No.	Temperature		Experimental Thermal Conductivity, Btu/hr-ft-F	Calculated*** Thermal Conductivity	
	F	C		Btu/hr-ft-F	cal/cm-sec-C $\times 10^4$
1	-29.1	-33.9	0.123	0.122	5.03
1	-8.2	-22.3	0.119	0.119	4.93
1	8.1	-13.3	0.116	0.117	4.85
1	25.3	-3.7	0.118	0.115	4.77
1	41.2	5.1	0.111	0.113	4.69
1	59.2	15.1	0.110	0.111	4.61
2	71.9	22.2	0.110	0.110	4.55
1	77.0	25.0	0.108	0.109	4.52
2	88.3	31.3	0.109	0.108	4.47
1	94.8	34.9	0.109	0.107	4.44
2	112.8	44.9	0.105	0.105	4.35
1	112.9	44.9	0.103	0.105	4.35
2	131.0	55.0	0.102	0.103	4.26
2	149.5	55.3	0.104	0.101	4.17
2	168.8	76.0	0.096	0.0985	4.08
2	185.6	85.3	0.098	0.0966	4.00

*Sample Compositions:

ClF_3 , w/o	99.7
HF, w/o	0.3

**Measurement series 1 and 2 used two different ClF_3 samples
and two different platinum wires.

***From curve-fit of the experimental data.

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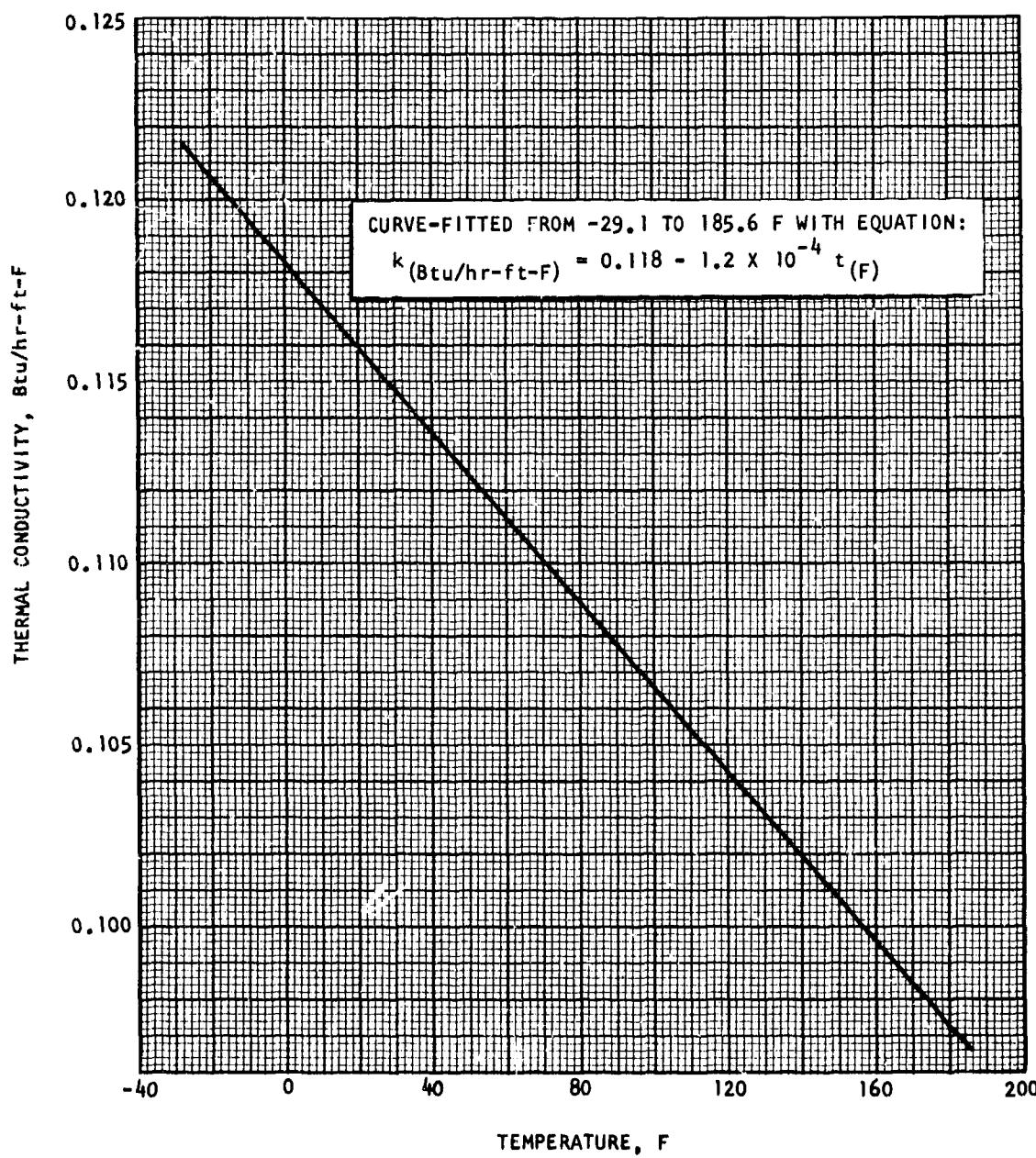


Figure 16. Thermal Conductivity of Saturated Liquid ClF_3

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(C) Thermal Conductivity of Florox. The thermal conductivity of Florox (ClF_3O) was measured over a temperature range of -23.8 to 154.6 F (-31.0 to 68.1 C) using the "hot-wire" transient measurement apparatus. The data obtained from these measurements are presented in Table 23 with the chemical analysis of the ClF_3O sample. A least squares curve-fit computer program was used to curve fit the measured values with the following linear expressions:

$$k_{(\text{Btu}/\text{hr}\cdot\text{ft}\cdot\text{F})} = 0.1022 - 5.53 \times 10^{-5}t_{(\text{F})}$$

and

$$k_{(\text{cal}/\text{cm}\cdot\text{sec}\cdot\text{C})} = 4.153 \times 10^{-4} - 4.114 \times 10^{-7}t_{(\text{C})}$$

The standard errors of estimate of these curve fits, which are graphically represented in Fig. E-5 of Appendix E, are 0.75 percent.

(C) Thermal Conductivity of MOR-5. The "hot-wire" apparatus was used to measure the thermal conductivity of MOR-5 (nominal composition: 78 w/o ClF_3O - 22 w/o ClF_5) over the temperature range of -28.6 to 130.3 F (-33.7 to 54.6 C). Least-squares computer curve-fits of the experimental data, which are shown in Table 24 with the sample composition, resulted in the following expressions:

$$k_{(\text{Btu}/\text{hr}\cdot\text{ft}\cdot\text{F})} = 0.1075 - 3.20 \times 10^{-5}t_{(\text{F})} - 5.17 \times 10^{-7}t_{(\text{F})}^2$$

and

$$k_{(\text{cal}/\text{cm}\cdot\text{sec}\cdot\text{C})} = 4.38 \times 10^{-4} - 4.85 \times 10^{-7}t_{(\text{C})} - 6.93 \times 10^{-9}t_{(\text{C})}^2$$

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TABLE 23

THERMAL CONDUCTIVITY DATA ON SATURATED LIQUID FLOROX*

Temperature		Experimental Thermal Conductivity, Btu/hr-ft-F	Calculated** Thermal Conductivity	
F	C		Btu/hr-ft-F	cal/cm-sec-C x 10 ⁴
-23.8	-31.0	0.1029	0.1035	4.281
-7.5	-21.9	0.1023	0.1027	4.246
8.2	-13.2	0.1034	0.1017	4.267
25.8	-3.4	0.1008	0.1009	4.172
42.0	5.6	0.1003	0.0999	4.131
59.0	15.0	0.0982	0.0990	4.092
77.0	25.0	0.0976	0.0980	4.051
94.6	34.8	0.0965	0.0970	4.011
115.2	46.2	0.0965	0.0959	3.963
134.8	57.1	0.0947	0.0948	3.919
154.6	68.1	0.0936	0.0937	3.874

*Sample Composition:

ClF ₃ 0, w/o	99.7
ClF ₃ , w/o	0.1
FC10 ₃ , w/o	0.1
HF, W/o	0.1

**From curve-fit of experimental data.

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TABLE 24

THERMAL CONDUCTIVITY DATA ON SATURATED LIQUID MOR-5*

Temperature		Experimental Thermal Conductivity, Btu/hr-ft-F	Calculated** Thermal Conductivity	
F	C		Btu/hr-ft-F	cal/cm-sec-C x 10 ⁴
-28.6	-33.7	0.109	0.108	4.47
-11.8	-24.3	0.107	0.108	4.46
6.8	-14.0	0.107	0.107	4.44
23.4	-4.8	0.106	0.106	4.40
41.3	5.2	0.104	0.105	4.36
59.2	15.1	0.104	0.104	4.30
76.6	24.8	0.104	0.102	4.22
94.5	34.7	0.100	0.0998	4.13
112.6	44.8	0.097	0.0973	4.03
130.3	54.6	0.094	0.0945	3.91

*Sample Composition:

ClF ₃ ⁰ , w/o	77.5
ClF ₅ , w/o	21.7
ClF ₃ , w/o	0.6
FC1O ₂ , w/o	0.2

**From curve-fit of experimental data.

The standard errors of estimate of these expressions, which are represented graphically in Fig. F-6 and F-6a of Appendix F, are 0.001 Btu/hr-ft-F and 4.4×10^{-6} cal/cm-sec-C, respectively.

(U) Thermal Conductivity of MHF-7. Thermal conductivity measurements were conducted on MHF-7 formulations -N, -1, and -2 (see the "Propellant Formulation and Chemical Analyses" section) using the "hot-wire" cell fabricated from aluminum. The resulting data, covering the temperature range of -16.8 to 162.2 F (-27.1 to 72.3 C), are given in Table 25 with the corresponding sample analyses. These data were curve-fitted by a least squares computer program with the following expressions of thermal conductivity (k) as a function of temperature (t) and composition in weight percent (w/o) N_2H_4 (H) and H_2O (W):

$$\begin{aligned} k(\text{Btu/hr-ft-F}) = & 4.005 \times 10^{-2} + 2.229 \times 10^{-3} t(F) - 1.09 \times 10^{-5} t(F)^2 \\ & + 4.82 \times 10^{-3} H(w/o) + 1.30 \times 10^{-4} W(w/o) \\ & - 6.11 \times 10^{-5} H(w/o) t(F) - 3.28 \times 10^{-5} W(w/o) t(F) \\ & + 2.1 \times 10^{-7} H(w/o) t(F)^2 + 3.1 \times 10^{-7} W(w/o) t(F)^2 \end{aligned}$$

and

$$\begin{aligned} k(\text{cal/cm-sec-C}) = & 4.142 \times 10^{-4} + 1.138 \times 10^{-5} t(C) - 1.46 \times 10^{-7} t(C)^2 \\ & + 1.273 \times 10^{-5} H(w/o) - 2.48 \times 10^{-6} W(w/o) \\ & - 3.55 \times 10^{-7} H(w/o) t(C) - 9.5 \times 10^{-8} W(w/o) t(C) \\ & + 2.8 \times 10^{-9} H(w/o) t(C)^2 + 4.2 \times 10^{-9} W(w/o) t(C)^2 \end{aligned}$$

The standard errors of estimate of these expressions, which are represented graphically (for the nominal formulation) in Fig. G-6 and G-6a of Appendix G, are 4.1×10^{-3} Btu/hr-ft-F and 1.7×10^{-5} cal/cm-sec-C, respectively.

TABLE 25
THERMAL CONDUCTIVITY DATA ON LIQUID MHF-7

Formulation	Temperature		Experimental Thermal Conductivity, Btu/hr-ft-F	Calculated* Thermal Conductivity	
	F	C		Btu/hr-ft-F	cal/cm-sec-C x 10 ⁴
MHF-7-N	74.00	23.3	0.1672	0.1632	6.747
MHF-7-N	74.00	23.3	0.1655	0.1632	6.747
MHF-7-N	74.05	23.4	0.1654	0.1632	6.747
MHF-7-N	74.05	23.4	0.1627	0.1632	6.747
MHF-7-N	70.95	21.6	0.1655	0.1624	6.747
MHF-7-N	71.00	21.6	0.1665	0.1624	6.714
MHF-7-N	71.00	21.7	0.1730	0.1624	6.714
MHF-7-N	71.05	21.7	0.1672	0.1624	6.715
MHF-7-N	53.60	12.0	0.1631	0.1555	6.430
MHF-7-N	53.60	12.0	0.1620	0.1555	6.430
MHF-7-N	53.60	12.0	0.1620	0.1555	6.430
MHF-7-N	53.60	12.0	0.1603	0.1555	6.430
MHF-7-N	35.30	1.8	0.1442	0.1439	5.951
MHF-7-N	35.30	1.8	0.1467	0.1439	5.951
MHF-7-N	35.25	1.8	0.1429	0.1439	5.949
MHF-7-N	35.25	1.8	0.1457	0.1439	5.949
MHF-7-N	17.30	-8.2	0.1265	0.1282	5.301
MHF-7-N	17.30	-8.2	0.1245	0.1282	5.301
MHF-7-N	17.30	-8.2	0.1236	0.1282	5.301
MHF-7-N	17.30	-8.2	0.1215	0.1282	5.301
MHF-7-N	2.50	-16.4	0.1076	0.1120	4.632
MHF-7-N	2.50	-16.4	0.1083	0.1120	4.632
MHF-7-N	2.50	-16.4	0.1080	0.1120	4.632
MHF-7-N	2.50	-16.4	0.1072	0.1120	4.632
MHF-7-N	-16.80	-27.1	0.0890	0.0866	3.581
MHF-7-N	-16.80	-27.1	0.0898	0.0866	3.581
MHF-7-N	-16.80	-27.1	0.0890	0.0866	3.581
MHF-7-N	-16.80	-27.1	0.0891	0.0866	3.581
MHF-7-N	88.50	31.4	0.1639	0.1653	6.833
MHF-7-N	88.50	31.4	0.1632	0.1653	6.833
MHF-7-N	88.50	31.4	0.1583	0.1653	6.833
MHF-7-N	88.50	31.4	0.1634	0.1653	6.833
MHF-7-N	106.40	41.3	0.1591	0.1640	6.780
MHF-7-N	106.40	41.3	0.1557	0.1640	6.780
MHF-7-N	106.40	41.3	0.1583	0.1640	6.780
MHF-7-N	106.40	41.3	0.1589	0.1640	6.780

TABLE 25
THERMAL CONDUCTIVITY DATA ON LIQUID MHF-7
(Continued)

Formulation	Temperature		Experimental Thermal Conductivity, Btu/hr-ft-F	Calculated* Thermal Conductivity	
	F	C		Btu/hr-ft-F	cal/cm-sec-C x 10 ⁴
MHF-7-N	124.70	51.5	0.1566	0.1583	6.545
MHF-7-N	124.70	51.5	0.1528	0.1583	6.545
MHF-7-N	124.70	51.5	0.1541	0.1583	6.545
MHF-7-N	124.70	51.5	0.1515	0.1583	6.545
MHF-7-N	143.60	62.0	0.1504	0.1477	6.108
MHF-7-N	143.60	62.0	0.1466	0.1477	6.108
MHF-7-N	143.60	62.0	0.1541	0.1477	6.108
MHF-7-N	143.60	62.0	0.1484	0.1477	6.108
MHF-7-N	162.20	72.3	0.1362	0.1327	5.487
MHF-7-N	162.20	72.3	0.1383	0.1327	5.487
MHF-7-1	77.4	25.2	0.1642	0.1616	6.682
MHF-7-1	77.4	25.2	0.1610	0.1616	6.682
MHF-7-1	77.4	25.2	0.1613	0.1616	6.682
MHF-7-1	60.4	15.8	0.1603	0.1556	6.435
MHF-7-1	60.4	15.8	0.1582	0.1556	6.435
MHF-7-1	76.0	24.4	0.1643	0.1612	6.666
MHF-7-1	76.0	24.4	0.1616	0.1612	6.666
MHF-7-1	42.3	5.7	0.1494	0.1461	6.041
MHF-7-1	42.3	5.7	0.1486	0.1461	6.041
MHF-7-1	24.2	-4.3	0.1322	0.1333	5.513
MHF-7-1	24.2	-4.3	0.1285	0.1333	5.513
MHF-7-1	6.2	-14.3	0.1166	0.1174	4.853
MHF-7-1	6.2	-14.3	0.1127	0.1174	4.853
MHF-7-1	-11.2	-24.0	0.1003	0.0989	4.089
MHF-7-1	-11.2	-24.0	0.1009	0.0989	4.089
MHF-7-1	95.0	35.0	0.1607	0.1648	6.812
MHF-7-1	95.0	35.0	0.1635	0.1648	6.812
MHF-7-1	113.7	45.4	0.1607	0.1647	6.811
MHF-7-1	113.7	45.4	0.1628	0.1647	6.811
MHF-7-1	132.3	55.7	0.1603	0.1612	6.666
MHF-7-1	132.3	55.7	0.1584	0.1612	6.666
MHF-7-1	150.1	65.6	0.1586	0.1547	6.395
MHF-7-1	150.1	65.6	0.1534	0.1547	6.395
MHF-7-1	160.7	71.5	0.1509	0.1493	6.171
MHF-7-1	160.7	71.5	0.1501	0.1493	6.171

TABLE 25
THERMAL CONDUCTIVITY DATA ON LIQUID MHF-7
(Concluded)

Formulation	Temperature		Experimental Thermal Conductivity, Btu/hr-ft-F	Calculated* Thermal Conductivity	
	F	C		Btu/hr-ft-F	cal/cm-sec-C x 10 ⁴
MHF-7-2	81.4	27.4	0.1653	0.1705	7.051
MHF-7-2	81.4	27.4	0.1646	0.1705	7.051
MHF-7-2	63.5	17.5	0.1690	0.1685	6.968
MHF-7-2	63.5	17.5	0.1703	0.1685	6.968
MHF-7-2	45.4	7.4	0.1673	0.1629	6.734
MHF-7-2	45.4	7.4	0.1681	0.1629	6.734
MHF-7-2	27.5	-2.5	0.1595	0.1537	6.355
MHF-7-2	27.5	-2.5	0.1603	0.1537	6.355
MHF-7-2	9.4	-12.6	0.1393	0.1408	5.821
MHF-7-2	9.4	-12.6	0.1382	0.1408	5.821
MHF-7-2	-8.0	-22.2	0.1218	0.1250	5.167
MHF-7-2	-8.0	-22.2	0.1217	0.1250	5.167
MHF-7-2	98.8	37.1	0.1659	0.1691	6.991
MHF-7-2	98.8	37.1	0.1679	0.1691	6.991
MHF-7-2	117.5	47.5	0.1619	0.1638	6.772
MHF-7-2	117.5	47.5	0.1609	0.1638	6.772
MHF-7-2	134.3	56.8	0.1570	0.1557	6.438
MHF-7-2	134.3	56.8	0.1541	0.1557	6.438
MHF-7-2	149.9	65.5	0.1502	0.1454	6.011
MHF-7-2	149.9	65.5	0.1473	0.1454	6.011

SAMPLE COMPOSITIONS

Formulation	CH ₃ N ₂ H ₃ , w/o	N ₂ H ₄ , w/o	H ₂ O, w/o	Other Soluble Impurities, w/o
MHF-7-N	81.3	14.2	4.2	0.3
MHF-7-1	75.9	14.5	9.3	0.3
MHF-7-2	76.2	19.1	4.4	0.3

*From curve-fit of experimental data.

(U) As noted in Fig. G-6 and G-6a, the thermal conductivity of the nominal formulation rises (as temperature is increased) to a peak at a temperature level of ~ 98 F (~ 37 C), where it begins to decrease. All MHr-7 formulations exhibited this peak in the temperature level area of ~ 100 F (depending on the composition) and this parabolic behavior is reflected in the curve-fit expressions.

Sonic Velocity Measurements

(U) Sonic velocity measurements were conducted in MON-25, Florox, N_2H_4 , MMH, UDMH, 50 N_2H_4 - 50 UDMH, MHF-3, MHF-5, and MHF-7 under saturated liquid conditions over selected temperature ranges. The resulting data were then used to calculate the adiabatic compressibilities of these propellants (as noted in the "Adiabatic Compressibility" section).

(U) Sonic velocity measurements in MON-25 and Florox were conducted in the experimental apparatus, which has been described previously in Ref. 2 and is illustrated in Fig. 17. This apparatus accurately measures the distance which sound waves of a known frequency travel through a test fluid. The interferometer, which is capable of withstanding pressures to 1000 psia and temperatures to 200 F, is constructed of type 347 stainless steel. The dial gage, which provides precise linear location data, also enables the differentiation between the reflected signal (and its harmonics) and reflections from the metallic interferometer body. Displayed pips, from true reflections, move on the oscilloscope as the reflector is moved, while spurious signals remain stationary.

(U) The measurements are conducted by initiation of a 5-megahertz radio frequency signal from the pulsed oscillator, which is fed simultaneously to the oscilloscope and a quartz piezoelectric crystal (with 5-megahertz resonant frequency) attached to the bottom of the interferometer. The sound waves, emanating from the crystal, travel through the bottom

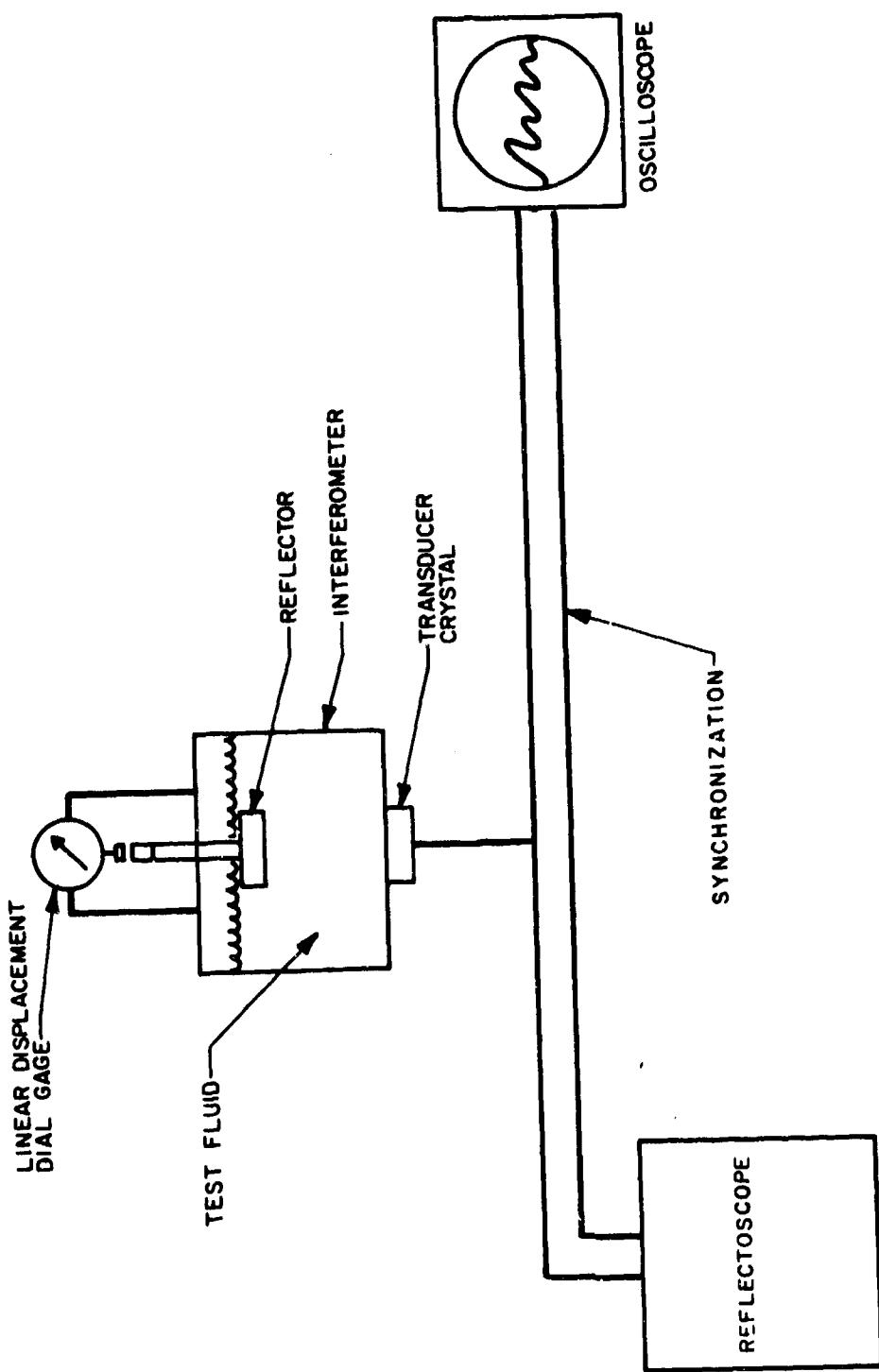


Figure 17. Sonic Velocity Apparatus for Oxidizers

of the interferometer, through a known distance of test liquid to a reflector, and then back to the crystal. The initial and reflected waves are displayed on the oscilloscope, thus allowing measurement of the time required for the ultrasonic waves to traverse the known distance of test fluid.

- (U) During the determinations, the interferometer was immersed in a constant-temperature bath and allowed to reach thermal equilibrium at a selected temperature level before a measurement was conducted. The equilibrium temperature was then measured using a chromel-alumel thermocouple (with a type 316 stainless-steel sheath) immersed in the test fluid.
- (U) The sonic velocity apparatus was calibrated over a temperature range of 0 to 60.4 C (37.0 to 140.7 F) with distilled water, and from -26.0 to 25.0 C (14.8 to 77.0 F) with absolute methanol as test fluids. The data obtained from sonic velocity measurements in these fluids with this apparatus were compared with literature values for these fluids (Ref. 16 and 17) to obtain a calibration factor.
- (U) Sonic velocity measurements in the hydrazine-type fuels were conducted in the sonic velocity cell illustrated in Fig. 18. This cell was fabricated from aluminum alloy 6061 which is more compatible with this class of fuels, particularly at the high temperatures covered in the measurements. The associated electronic equipment and measurement technique used in conjunction with the previously described cell also apply to this apparatus.

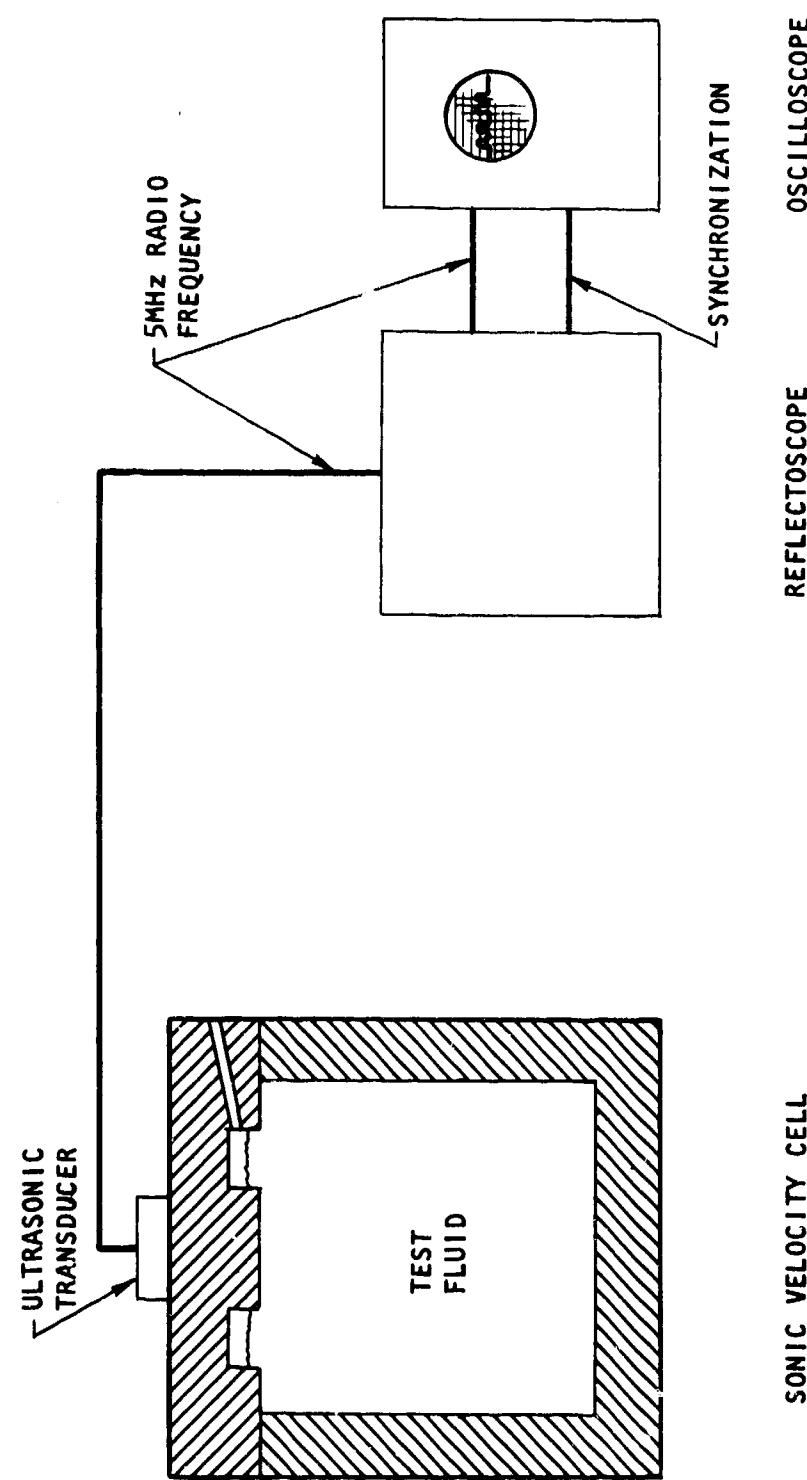


Figure 18. Sonic Velocity Apparatus for Fuels

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(U) Sonic Velocity in MON-25. Measurements of the velocity of sound in MON-25 (nominal composition: 75 w/o N_2O_4 - 25 w/o NO) were conducted over the temperature range of -51.4 to 86.9 C (-60.5 to 188.4 F) under saturated liquid conditions. The resulting data (shown in Table 26 with the sample analyses) were curve-fitted by a least squares computer program with the following expressions of sonic velocity (c) as a function of temperature (t):

$$c(\text{m/sec}) = 1153 - 4.281 t(\text{C}) - 2.725 \times 10^{-3} t(\text{C})^2$$

and

$$c(\text{ft/sec}) = 4030 - 7.626 t(\text{F}) - 2.76 \times 10^{-3} t(\text{F})^2$$

The standard errors of estimate for these expressions, which are represented graphically in Fig. C-8 and C-8a of Appendix C, are 4.4 m/sec and 14.6 ft/sec, respectively.

(C) Sonic Velocity in Florox. Sonic velocity measurements were conducted in saturated liquid Florox (ClF_3O) over a temperature range of -31.0 to 61.4 C (-23.8 to 142.6 F). The results of these measurements and the composition of the propellant sample are given in Table 27. These data were curve-fit using a least squares computer program to give the following equations:

$$c(\text{m/sec}) = 918.0 - 3.516 t(\text{C})$$

and

$$c(\text{ft/sec}) = 3217.0 - 6.409 t(\text{F})$$

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TABLE 26

SONIC VELOCITY IN SATURATED LIQUID MON-25*

Temperature		Sonic Velocity, m/sec		Sonic Velocity, ft/sec
C	F	Actual	Calculated	Calculated
-51.4	-60.5	1365	1366	4481
-51.4	-60.5	1372	1366	4481
-34.7	-30.5	1292	1298	4260
-31.9	-25.4	1281	1287	4222
-9.8	14.4	1198	1195	3920
4.3	39.7	1143	1135	3722
10.0	50.0	1111	1110	3642
14.4	57.9	1096	1091	3579
19.1	66.4	1064	1070	3511
24.3	75.7	1045	1047	3436
26.8	80.2	1034	1036	3400
29.4	90.9	1022	1025	3362
31.3	88.3	1018	1016	3335
32.9	91.2	1008	1009	3311
53.2	127.8	918	918	3010
60.6	141.1	884	884	2899
65.5	149.9	863	861	2825
76.5	169.7	808	810	2656
78.7	173.7	799	799	2622
82.0	179.6	781	784	2571
85.0	185.0	777	769	2525
86.9	188.4	756	760	2495

*Sample Composition:

 N_2O_4 , w/o 75.3
NO, w/o 24.7

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TABLE 27

SONIC VELOCITY IN SATURATED LIQUID FLOROX*

Temperature		Sonic Velocity, m/sec		Sonic Velocity, ft/sec
C	F	Actual	Calculated	Calculated
-31.0	-23.8	1025.4	1027.1	3369.5
-13.4	7.9	966.5	965.2	3166.5
-10.7	12.7	953.7	955.7	3135.4
0.0	32.0	917.7	918.0	3011.9
1.3	34.3	916.7	913.5	2996.9
4.4	39.9	901.8	902.6	2961.2
13.8	56.8	872.5	869.5	2852.7
17.1	62.8	862.8	857.9	2814.7
23.6	74.5	831.5	835.1	2739.7
24.9	76.8	829.7	830.5	2724.7
26.3	79.3	825.3	825.6	2708.5
31.6	38.9	804.8	806.9	2647.4
38.7	101.7	780.6	782.0	2565.5
44.4	111.9	761.5	761.9	2499.7
49.9	121.8	741.2	742.6	2436.3
56.0	132.8	720.6	721.1	2365.9
61.4	142.6	704.9	702.1	2303.1

*Sample Composition:

C₁F₃⁰, w/o 99.7
C₁F₃, w/o 0.1
FC₁O₂, w/o 0.1
HF, w/o 0.1

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The standard errors of estimate for these equations are 2.3 m/sec and 7.7 ft/sec, respectively. The expressions are graphically represented in Fig. E-6 and E-6a of Appendix E.

(U) Sonic Velocity in N_2H_4 . Sonic velocities were measured in propellant-grade hydrazine (N_2H_4) over a temperature range of 6.1 to 96.5 C (43.0 to 205.7 F) under saturated liquid conditions. The resulting data, shown in Table 28 with the sample composition, were curve-fit by a least squares computer program with the following equations:

$$c(\text{m/sec}) = 2178.6 - 4.539t(\text{C}) + 6.60 \times 10^{-3}t(\text{C})^2$$

and

$$c(\text{ft/sec}) = 7419.1 - 8.701t(\text{F}) + 6.68 \times 10^{-3}t(\text{F})^2$$

The standard errors of estimate for these equations are 4.4 m/sec and 14.4 ft/sec, respectively. The metric system expression is graphically represented in Fig. 19.

(U) Sonic Velocity in MMH. Measurements of the velocity of sound in propellant-grade (composition given in Table 29) monomethylhydrazine (MMH or $CH_3N_2H_3$) were conducted over the temperature range of -31.9 to 95.6 C (-25.4 to 204.1 F) under saturated liquid conditions. The resulting data (Table 29) were curve-fit by a least squares computer program and the resulting equations (represented graphically in Fig. A-10 and A-10a of Appendix A) are as follows:

TABLE 28

SONIC VELOCITY IN SATURATED LIQUID N_2H_4 *

Temperature		Sonic Velocity, m/sec		Sonic Velocity, ft/sec
C	F	Actual	Calculated	Calculated
6.1	43.0	2146.0	2151.1	7057.5
25.0	77.0	2071.1	2069.2	6788.8
37.8	100.0	2022.3	2016.4	6615.6
57.2	135.0	1938.4	1940.5	6366.6
64.5	148.1	1916.8	1913.3	6277.1
73.5	164.3	1874.9	1880.6	6169.9
73.5	164.3	1872.6	1880.6	6169.9
93.0	199.4	1811.0	1813.5	5949.8
94.2	201.6	1815.3	1809.5	5936.8
96.5	205.7	1804.7	1802.0	5912.0

*Sample Composition:

N_2H_4 , w/o	98.3
H_2O , w/o	0.9
NH_3 , w/o	0.2
Aniline, w/o	0.6

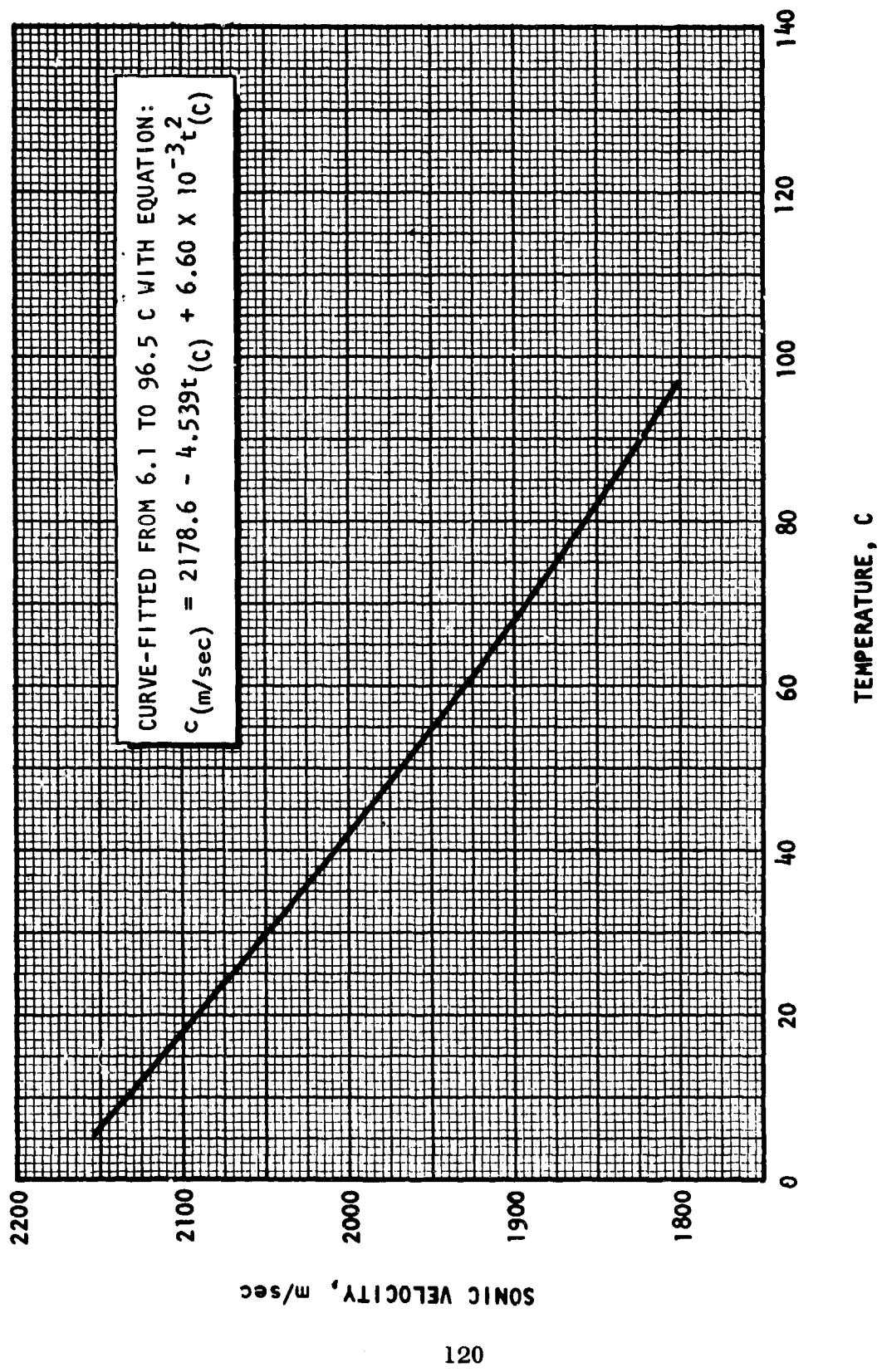


Figure 19. Velocity of Sound in Saturated Liquid Hydrazine.

TABLE 29

SONIC VELOCITY IN SATURATED LIQUID MMH*

Temperature		Sonic Velocity, m/sec		Sonic Velocity, ft/sec
C	F	Actual	Calculated	Calculated
-31.9	-25.4	1773.2	1771.0	5810.3
0	32.0	1643.2	1646.5	5401.9
25.0	77.0	1546.1	1548.9	5081.8
25.0	77.0	1547.6	1548.9	5081.8
37.8	100.0	1499.5	1499.0	4917.9
37.8	100.0	1506.8	1499.0	4917.9
73.5	164.3	1353.5	1359.7	4460.9
87.5	189.5	1303.2	1305.0	4281.6
95.6	204.1	1278.4	1273.4	4177.9

*Sample Composition:

CH ₃ N ₂ H ₃ , w/o	99.5
H ₂ O, w/o	0.4
Other Soluble Impurities, w/o	0.1

$$c \text{ (m/sec)} = 1646.5 - 3.902t \text{ (C)}$$

and

$$c \text{ (ft/sec)} = 5629.5 - 7.113t \text{ (F)}$$

The standard errors of estimate for these expressions are 4.1 m/sec and 13.5 ft/sec, respectively.

(U) Sonic Velocity in UDMH. Sonic velocity measurements were conducted in propellant-grade (composition given in Table 30) unsymmetrical dimethylhydrazine [UDMH or $(\text{CH}_3)_2\text{N}_2\text{H}_2$] over the temperature range of -37.3 to 93.0 C (-35.1 to 199.4 F). The resulting data (Table 30) were curve-fit by a least squares computer program with the following equations:

$$c \text{ (m/sec)} = 1360.3 - 4.513t \text{ (C)}$$

and

$$c \text{ (ft/sec)} = 4726.2 - 8.225t \text{ (F)}$$

Standard errors of estimate for these equations were 3.3 m/sec and 10.7 ft/sec, respectively. The metric expression is graphically represented in Fig. 20.

(U) Sonic Velocity in 50 N_2H_4 - 50 UDMH. The sonic velocity in the 50 w/o N_2H_4 -50 w/o UDMH fuel blend was measured over a temperature range of 0.0 to 94.5 C (32.0 to 202.1 F) under saturated liquid conditions. The resulting data (shown in Table 31 with the sample composition) were curve-

TABLE 30
SONIC VELOCITY IN SATURATED LIQUID UDMH*

Temperature		Sonic Velocity, m/sec		Sonic Velocity, ft/sec
C	F	Actual	Calculated	Calculated
-37.3	-35.1	1532.0	1528.6	5015.2
0.0	32.1	1361.9	1360.3	4463.0
25.0	77.0	1244.0	1247.5	4092.9
25.0	77.0	1243.4	1247.5	4092.9
37.8	100.0	1186.9	1189.8	3903.4
73.8	164.8	1032.1	1027.3	3370.4
93.0	199.4	941.4	940.7	3086.1

*Sample Composition:

$(CH_3)_2N_2H_2$, w/o 99.7

H_2O , w/o 0.2

Other Soluble Impurities, w/o 0.1

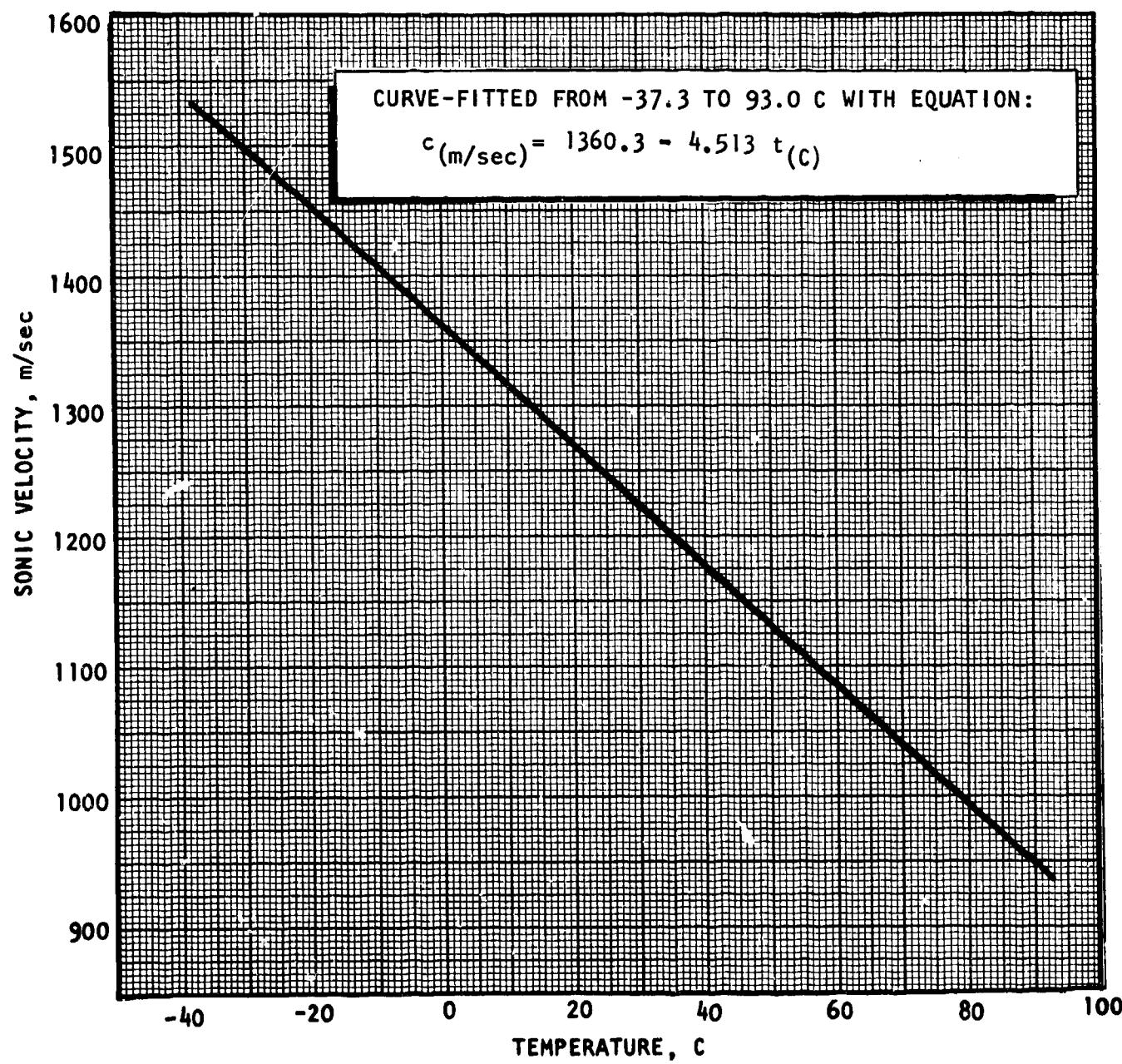


Figure 20. Velocity of Sound in Saturated Liquid UDMF

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TABLE 31

SONIC VELOCITY IN SATURATED LIQUID 50 W/O N_2H_4 -50 W/O UDMH*

Temperature		Sonic Velocity, m/sec		Sonic Velocity, ft/sec
C	F	Actual	Calculated	Calculated
0.0	32.0	1714.4	1710.3	5611.1
0.0	32.0	1718.3	1710.3	5611.1
13.4	56.1	1566.6	1659.6	5444.8
25.0	77.0	1608.5	1615.7	5300.9
25.0	77.0	1607.3	1615.7	5300.9
25.0	77.0	1610.6	1615.7	5300.9
34.9	94.8	1577.7	1578.3	5178.0
37.8	100.0	1568.1	1567.3	5142.0
37.8	100.0	1566.5	1567.3	5142.0
53.4	128.1	1512.8	1508.3	4948.4
60.7	141.3	1476.6	1480.7	4857.8
60.8	141.4	1473.7	1480.3	4856.5
80.7	177.3	1409.1	1405.0	4609.5
80.7	177.3	1405.3	1405.0	4609.5
94.5	202.1	1359.5	3152.8	4438.2

*Sample Composition:

N_2H_4 , w/o	51.3
$(CH_3)_2N_2H_2$, w/o	48.1
H_2O Plus Other Insoluble Impurities, w/o	0.6

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fit by a least squares computer program with the following equations in the metric (graphically illustrated in Fig. 21) and English systems:

$$c(\text{m/sec}) = 1710.3 - 3.783t(\text{C})$$

and

$$c(\text{ft/sec}) = 5831.8 - 6.895t(\text{F})$$

The standard errors of estimate for these equations are 5.3 m/sec and 17.5 ft/sec, respectively.

(c) Sonic Velocity in MHF-3. Sonic velocity measurements were conducted in saturated liquid MHF-3 (nominal composition of 86 w/o MH - 14 w/o N_2H_4) over the temperature range of -35.7 to 95.1 C (-32.3 to 203.2 F). The resulting data (shown in Table 32 with the sample composition) were curve-fit with a least squares computer program with the following equations:

$$c(\text{m/sec}) = 1704.3 - 4.043t(\text{C})$$

and

$$c(\text{ft/sec}) = 5827.2 - 7.369t(\text{F})$$

The standard errors of estimate for these curve fits are 4.0 m/sec and 13.2 ft/sec, respectively. The metric system expression is represented graphically in Fig. 22.

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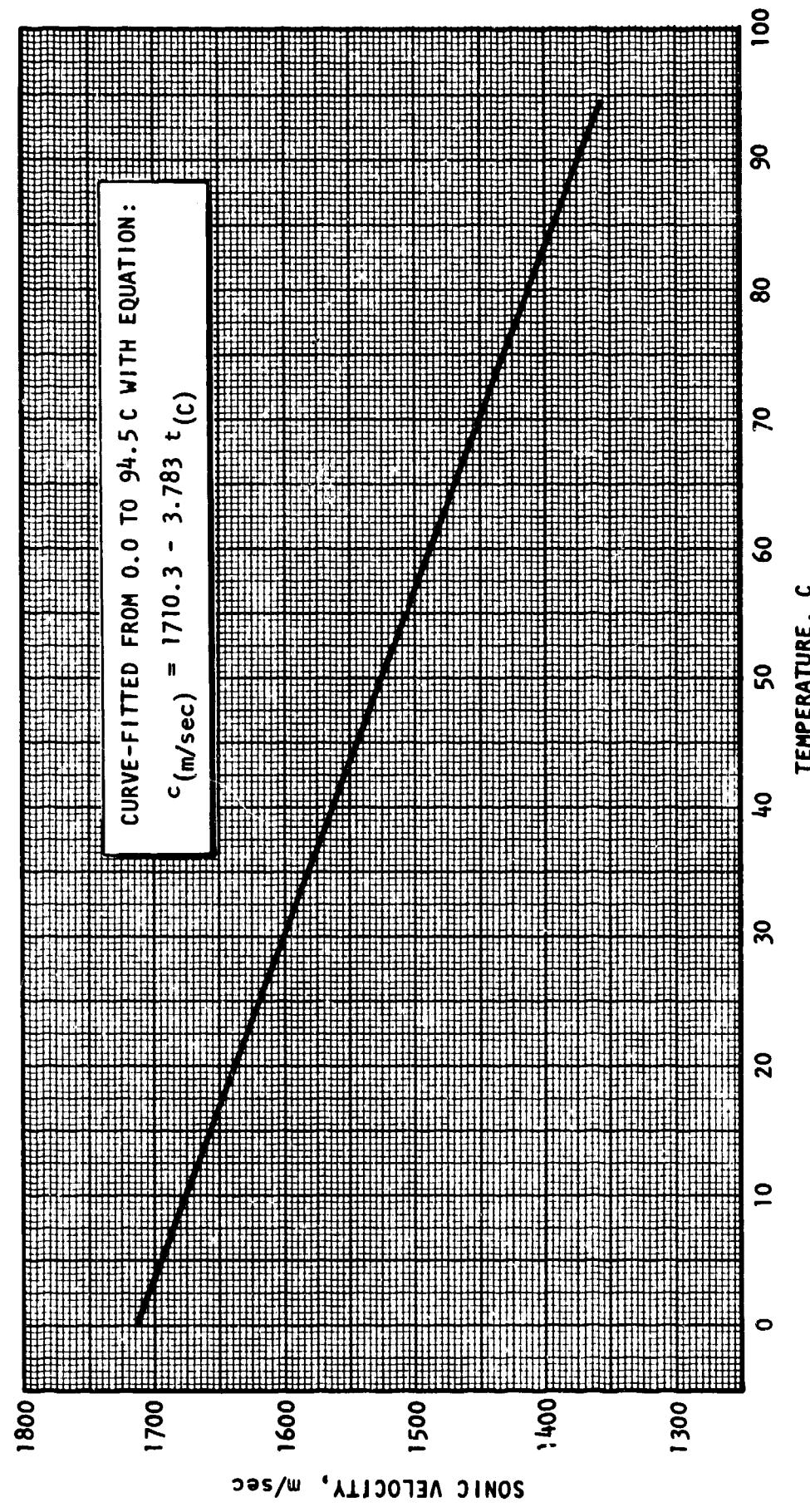


Figure 21. Velocity of Sound in Saturated Liquid 50 N₂H₄-50 UDMH

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TABLE 32

SONIC VELOCITY IN SATURATED LIQUID MHF-3*

Temperature		Sonic Velocity, m/sec		Sonic Velocity, ft/sec
C	F	Actual	Calculated	Calculated
-35.7	-32.3	1851.6	1848.6	6064.9
-21.9	-7.4	1787.4	1792.8	5881.8
-15.0	5.0	1761.4	1764.9	5790.3
0.0	32.0	1703.1	1704.3	5591.4
20.0	68.0	1627.6	1623.4	5326.1
25.0	77.0	1606.0	1603.2	5259.8
25.0	77.0	1604.0	1603.2	5259.8
40.0	104.0	1541.5	1542.6	5060.8
43.5	110.3	1524.7	1528.4	5014.4
59.6	139.3	1469.5	1463.3	4800.9
59.6	139.3	1468.6	1463.3	4800.9
81.1	178.0	1381.4	1376.4	4515.7
88.6	191.5	1341.7	1346.1	4416.2
88.6	191.5	1340.0	1346.1	4416.2
95.1	203.2	1317.7	1319.8	4330.0

*Sample Composition:

$\text{CH}_3\text{N}_2\text{H}_3$, w/o	85.6
N_2H_4 , w/o	13.9
NH_3 , w/o	0.4
H_2O , w/o	0.1

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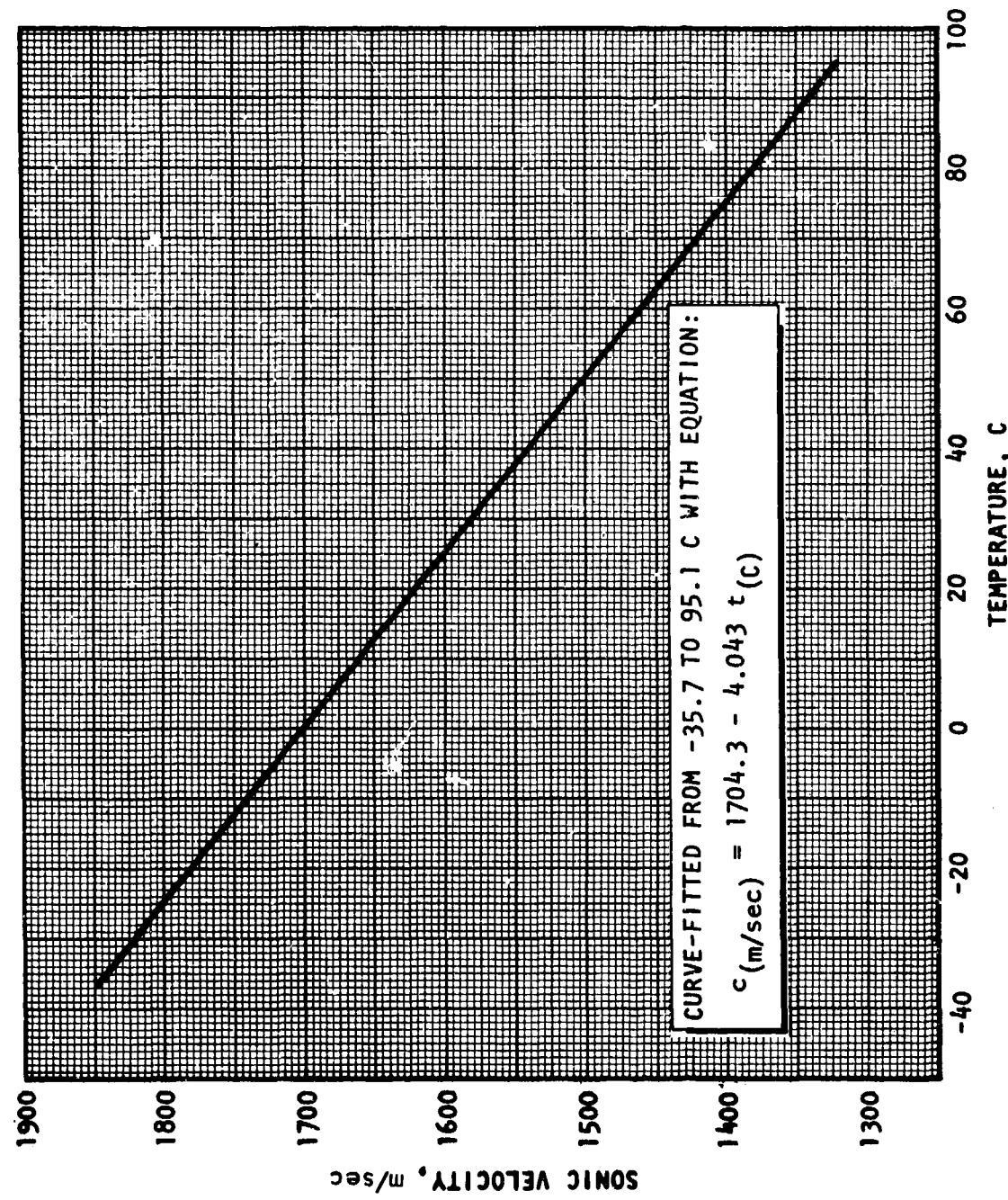


Figure 22. Velocity of Sound in Saturated Liquid MHF-3

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(C) Sonic Velocity in MHF-5. Sonic velocity measurements were conducted in saturated liquid MHF-5 (nominal composition of 55 w/o MMH - 26 w/o N_2H_4 - 19 w/o $N_2H_5NO_3$) over the temperature range of -39.4 to 95.0 C (-39.0 to 203.0 F). The resulting data (shown in Table 33 with the sample composition) were curve-fit by a least squares computer program with the following equations:

$$c(\text{m/sec}) = 1873.3 - 3.305t(\text{C})$$

and

$$c(\text{ft/sec}) = 6338.6 - 6.025t(\text{F})$$

The standard errors of estimate for these curve fits are 4.6 m/sec and 15.2 ft/sec. The metric system expression is represented graphically in Fig. 23.

(U) Sonic Velocity in MHF-7. Sonic velocity measurements were conducted in MHF-7 formulations -N, -1, and -2 (see "Propellant Formulation and Chemical Analyses" section) over the temperature range of -2.0 to 180.2 F (-18.9 to 82.3 C). The resulting data (shown in Table 34 with the sample compositions) were correlated with the data from measurements in MHF-3 (Table 32) by a least-squares curve-fit computer program. This correlation resulted in the following expressions of sonic velocity (c) as a function of temperature (t) and composition in weight percent (w/o) N_2H_4 (H) and H_2O (W):

$$c(\text{m/sec}) = 1618.5 - 4.003t(\text{C}) + 5.96H(\text{w/o}) + 7.56W(\text{w/o})$$

and

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TABLE 33

SONIC VELOCITY IN SATURATED LIQUID MHF-5*

Temperature		Sonic Velocity, m/sec		Sonic Velocity, ft/sec
C	F	Actual	Calculated	Calculated
-39.4	-39.0	2006.5	2003.5	6573.1
-28.3	-18.9	1968.1	1966.8	6452.7
-25.3	-13.6	1955.6	1956.9	6420.2
-14.4	6.0	1919.2	1921.2	6303.1
0.0	32.0	1870.3	1873.3	6145.8
10.0	50.0	1841.3	1840.2	6037.4
19.5	67.0	1806.8	1809.1	5935.5
24.7	76.5	1788.0	1791.6	5878.0
37.8	100.0	1747.5	1748.3	5735.9
57.5	135.5	1693.7	1683.2	5522.3
81.1	178.0	1610.7	1605.2	5266.4
95.0	203.0	1550.8	1559.3	5115.6

* Sample Composition:

$\text{CH}_3\text{N}_2\text{H}_3$, w/o	54.3
N_2H_4 , w/o	25.4
$\text{N}_2\text{H}_5\text{NO}_3$, w/o	19.7
H_2O , w/o	0.6

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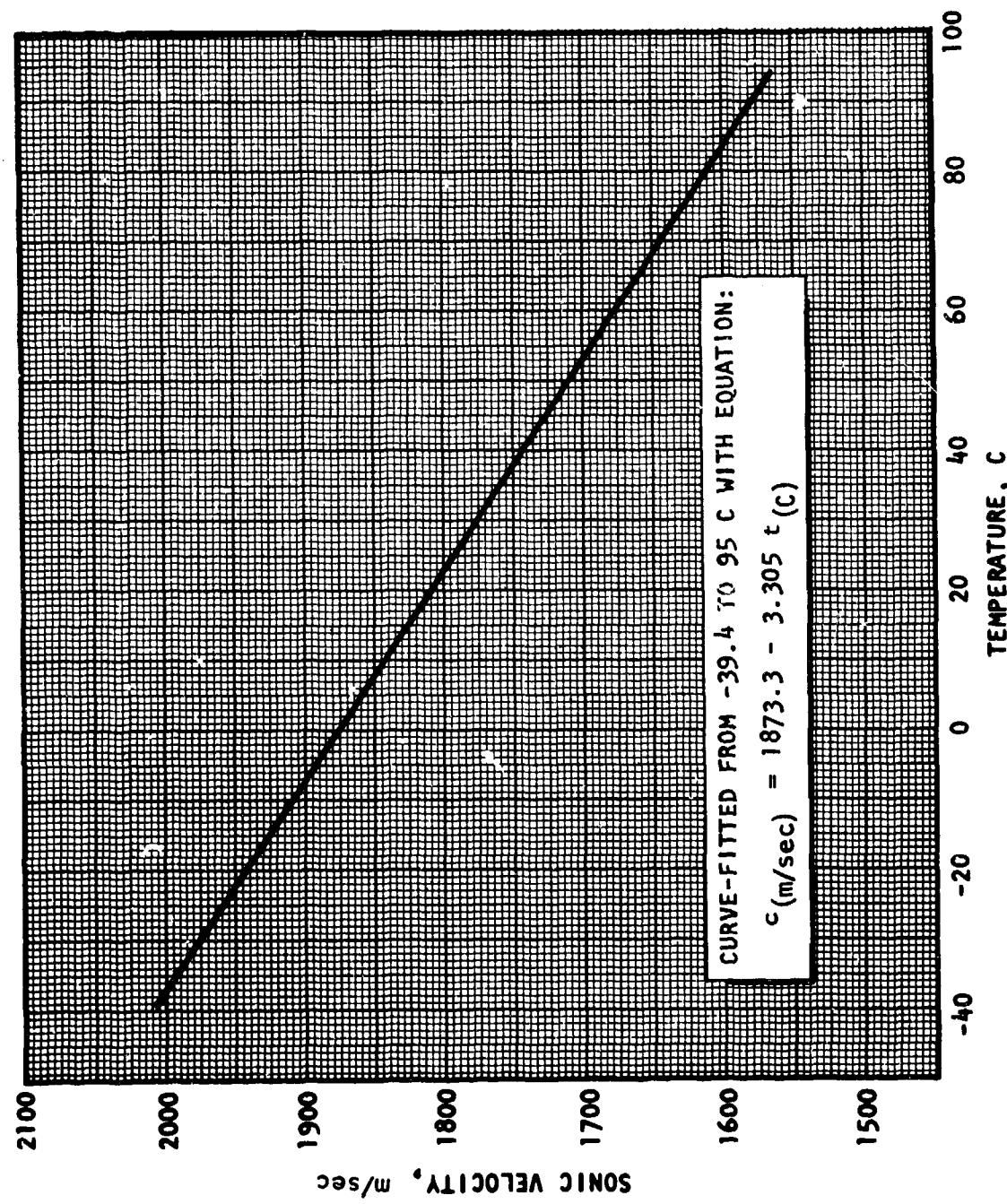


Figure 23. Velocity of Sound in Saturated Liquid MHF-5

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TABLE 34
SONIC VELOCITY IN SATURATED LIQUID MHF-7

Formulation	Temperature		Sonic Velocity, m/sec		Sonic Velocity, ft/sec
	C	F	Actual	Calculated	Calculated
MHF-7-N	-18.9	-2.0	1810	1810	5938
MHF-7-N	0.2	32.4	1725	1734	5689
MHF-7-N	15.4	59.8	1670	1673	5489
MHF-7-N	25.0	77.0	1630	1635	5364
MHF-7-N	48.9	120.0	1537	1539	5049
MHF-7-N	82.2	180.0	1405	1406	4613
MHF-7-1	-16.7	2.0	1838	1842	6043
MHF-7-1	0.1	32.2	1773	1775	5820
MHF-7-1	25.0	77.0	1678	1675	5495
MHF-7-1	49.2	120.5	1586	1578	5177
MHF-7-1	82.2	180.0	1450	1446	4744
MHF-7-2	-17.2	1.0	1834	1834	6017
MHF-7-2	0.0	32.0	1764	1766	5794
MHF-7-2	25.1	77.2	1667	1665	5463
MHF-7-2	48.9	120.0	1570	1570	5151
MHF-7-2	82.3	180.2	1436	1436	4711

SAMPLE COMPOSITIONS

Formulation	CH ₃ NH ₂ ^{3/2} , w/o	N ₂ H ₄ ^{1/2} , w/o	H ₂ O, w/o	Other Soluble Impurities, w/o
MHF-7-N	81.3	14.2	4.2	0.3
MHF-7-1	75.9	14.5	9.3	0.3
MHF-7-2	76.2	19.1	4.4	0.3

$$c(\text{ft/sec}) = 5543.4 - 7.296t(\text{F}) + 19.55H(\text{w/o}) + 24.80W(\text{w/o})$$

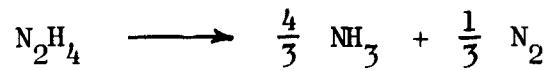
The standard errors of estimate of these expressions, represented graphically (for the nominal formulation) in Fig. G-7 and G-7a of Appendix G, are 4.4 m/sec and 14.3 ft/sec, respectively.

(U) Thermal Stability Measurements

(U) Preliminary thermal stability measurements were conducted on the 77 w/o N_2H_4 - 23 w/o $\text{N}_2\text{H}_5\text{N}_3$ monopropellant formulation using an experimental technique previously employed (Ref. 18) by Rocketdyne in similar determinations on hydrazine. In addition to these planned studies, a limited evaluation of the thermal stability of Florox was made during vapor pressure measurements. These studies are described in the following paragraphs.

(U) The experimental technique used to measure the thermal stability (as described in terms of liquid phase decomposition rate) of the N_2H_4 - $\text{N}_2\text{H}_5\text{N}_3$ formulation is described in detail in Ref. 18. In this technique, aliquots (0.3 ml) of the propellant sample were sealed in pyrex ampoules, which were then heated at a selected constant temperature level for a known period of time. In some of the experiments, the ampoule contained a section of passivated 321 stainless steel tubing with a surface area of 1 cm^2 . The amount of gaseous products (non-condensables in LN_2) was measured at the end of each experiment by opening the ampoule in a vacuum system, passing the products through a LN_2 trap, and determining the total pressure by means of a multirange McLeod gage. The reported percent decompositions were calculated using the assumption that $1/3$

mole of non-condensable gas is formed per mole of propellant decomposed, i.e.,



(U) The ampoules were cleaned in aqua regea, reused with distilled water, and dried. The stainless steel sections were boiled in trichloroethylene and dried. Then both the ampoules and metal tubes were passivated in liquid N_2H_4 at room temperature for 5 days, rinsed in distilled water, and dried. The ampoules were loaded with the propellant samples in a dry box and outgassed and sealed on a vacuum line.

(U) Thermal Stability of 77 w/o N_2H_4 - 23 w/o $\text{N}_2\text{H}_5\text{N}_3$. The liquid phase decomposition rate of the 77 w/o hydrazine (N_2H_4) - 23 w/o hydrazine azide ($\text{N}_2\text{H}_5\text{N}_3$) formulation (as described in the "Propellant Formulation and Chemical Analyses" section) was measured at 100 and 128 C (212 and 262.4 F, respectively) in contact with a stainless steel surface in pyrex, and at 172 C (342 F) in pyrex. Blank experiments were conducted with N_2H_4 for comparison purposes.

(U) Results in 321 Stainless Steel. The initial test on the N_2H_4 - $\text{N}_2\text{H}_5\text{N}_3$ formulation was conducted at 128 C (262.4 F) in contact with a passivated specimen of 321 stainless steel. The pyrex ampoule burst after 15 minutes in the 128 C bath, indicating (on the basis of previous quantitative estimates in Ref. 18) $\sim 5\%$ decomposition of the propellant. In comparison, the extrapolation of results from previous measurements (Ref. 18) indicates that the decomposition of propellant-grade N_2H_4 , $\text{N}_2\text{H}_4 + 1$ w/o NH_4NO_3 , and $\text{N}_2\text{H}_4 + 0.1$ w/o oxalic acid at 128 C over this period of time are 0.001%, 0.03%, and 0.2%, respectively.

(U) To obtain a more exact numerical value for the decomposition rate than that determined previously, the test temperature of the ampoules containing the formulation in contact with 321 stainless steel was reduced to 100 C (212 F). Triplicate 15-minute experiments at this temperature resulted in decomposition rates of 1.28, 1.48, and 1.24 percent per hour. Under these same conditions, the decomposition of propellant-grade N_2H_4 is 0.0004 percent per hour. Thus, the effect of the acidic ingredient is to increase the decomposition rate at 100 C by about a factor of 3000 in the presence of stainless steel. This is in approximate agreement with results obtained with other acidic additives to N_2H_4 (Ref. 18) but none of these other additives were tested above a concentration of 1-percent.

(U) Analysis of the non-condensable products from the run which gave a decomposition rate of 1.48 percent per hour showed a gas composition of 99.2 m/o N_2 and 0.8 m/o H_2 . This is the type of stoichiometry which is normally obtained with N_2H_4 decomposition (Ref. 18), indicating that the acidic azide probably catalyzes the decomposition of hydrazine. However, decomposition of the azide could also result in a high nitrogen gas composition.

(U) Results in Pyrex. Because only a small effect was expected from the azide in the absence of a metal surface, two initial 2-hour experiments were run in the pyrex ampoules at 172 C (342 F). Both of these ampoules broke, presumably from excessive decomposition of the propellant, but the exact time at which they broke was not observed. Duplicate 15-minute experiments at this temperature gave rates of 1.6 and 2.9 percent per hour. Under these conditions, the decomposition rate of propellant-

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grade N_2H_4 is 0.06 percent per hour. This increase in rate, of about a factor of 40 in the absence of metal, is slightly higher than that expected on the basis of previous results (Ref. 18) with other acidic additives to N_2H_4 (although none of these were tested at concentrations above 1 percent). It appears likely that the azine itself is decomposing at this temperature.

(U) Blank Experiments with N_2H_4 . During two blank experiments, with samples of the propellant-grade N_2H_4 used to prepare the $N_2H_4-N_2H_5N_3$ formulation, the same handling procedures and experimental conditions were used. The amount of gas measured in each of these two experiments (one with the metal specimen and one without) was about 1-percent of that obtained with the azide mixture. This confirms that the formulation containing the azide is much less stable than propellant-grade N_2H_4 . However, it should not be construed from these N_2H_4 blanks that the difference in stability is only a factor of 100. The gas measured in the blank experiments is mainly a fixed small quantity of gas which is present in all experiments regardless of length. With the longer heating times normally employed for propellant-grade N_2H_4 , this amount of gas is less than that which would be evolved at a decomposition rate of 0.0001 percent per hour.

(U) Significance of Results. Although these experiments demonstrate that the $N_2H_4-N_2H_5N_3$ formulation is much less stable than N_2H_4 at elevated temperatures, a number of factors should be considered in assessing the practicality of this propellant based on these results. These include:

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- (1) A metal surface of 3 cm^2 was present per milliliter of propellant
- (2) Only one metal was used and its cleaning and passivation procedure was not necessarily optimized
- (3) The activation energy of the acid-catalyzed reaction has not been measured so meaningful extrapolation to storage conditions cannot be made
- (4) Other propellants containing high concentrations of an acidic additive of (e.g., hydrazine nitrate) are storable at moderate temperatures.

On this basis, additional thermal stability studies, related to these considerations, are recommended for a more definitive evaluation of the thermal stability of the $\text{N}_2\text{H}_4\text{-N}_2\text{H}_5\text{N}_3$ formulation.

- (C) Thermal Stability of Florox. During vapor pressure measurements on Florox (ClF_3O), gas evolution was observed (during the measurement period) at temperatures above 120 C (248 F). A preliminary evaluation of the decomposition rate was accomplished by determinations of the total moles of gas (at -80 C) remaining in the type 304 stainless steel vapor pressure apparatus after the propellant sample had been maintained (for known periods of time) at various temperature levels ranging from 130 to 181 C (266 to 358 F). Decomposition rates (k_n), expressed as g-moles/cc (of liquid)-hr, were calculated and correlated with the following expression:

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$$\log k_n = 5.3595 - \frac{4270.6}{T(K)}$$

Because of the required assumptions that were made, this correlation represents only an "order-of-magnitude" estimate over the indicated temperature range. More detailed experiments would be required for a more accurate evaluation of the variables which enter into the decomposition rate.

Propellant Storability and Compatibility

- (U) Long-term, ambient-temperature storability tests on ClF_3 , ClF_5 , Florox, MHF-5, and MHF-7 have been initiated in potentially applicable metals of construction. Each of the storage containers used in these tests were fabricated entirely from the selected material following the design shown in Fig. 24. This construction eliminated bimetallic junctions and non-metallic sealants. Pressure transducers, fabricated from the same materials, are being used to monitor progress of the tests by measuring pressure rises caused by propellant reactions and/or decomposition. Readout of the pressure transducers is being accomplished by 500 μ a panel meters driven by operational amplifiers.
- (U) In fabrication of the storability containers, the two halves of each container (Fig. 24) were machined from bar stock of the indicated materials. The halves were joined by electron beam welding with 100% penetration (some weld drop-through was observed on the inside surface). Tungsten-inert gas welding was used to attach the fill tubes and transducers. The transducers, fill tubes, and Swagelok plugs were fabricated from the same materials as the container, with one exception, the pressure transducers for the 2219 Al containers were fabricated from 2024 Al.

AVERAGE CONTAINER VOLUME

ALL CONTAINERS (EXCEPT
FOR 1100 A1) - 595 CC
1100 A1 CONTAINERS - 550 CC

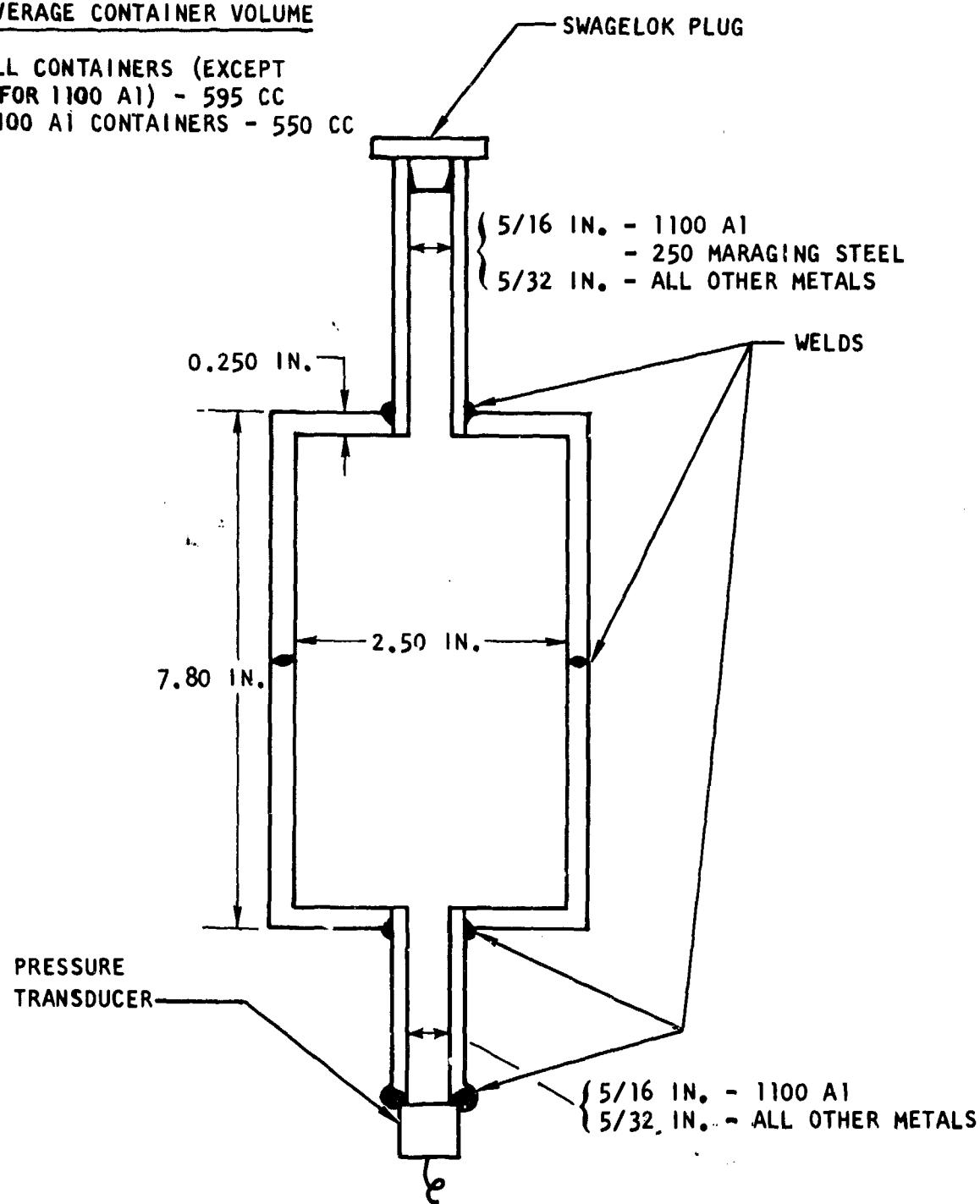


Figure 24. Storability Test Container

(U) The container parts were vapor degreased with perchloroethylene prior to welding. After welding, the containers were degreased with liquid trichloroethylene. Further surface (internal) preparations are described as follows:

1100 Al & 2219 Al

Treated with Aluminetch #2 for 5 minutes, rinsed with deionized water, dioxidized with Diverse 514 for 10 minutes, rinsed with deionized water, and dried.

321 SS, Inconel 718, & Hastelloy C

Alkaline cleaned with Turco Vitroklene for 15 minutes at 185 F, rinsed with deionized water, treated with 25% HNO_3 - 4% HF water solution for 30 minutes, rinsed with deionized water, and dried.

Maraging Steel 250

Sandblasted with alumina

Titanium 6Al-4V

Alkaline cleaned with 6-8 oz. of NA3-5163 cleaner/gal water solution for 10-20 minutes at 170-200 F, rinsed with deionized water, cleaned with 35-45% HNO_3 water solution for 1-2 minutes at 75 \pm 15 F, rinsed with deionized water, and dried.

Following the cleaning procedures, the containers were maintained in a clean, dry state.

(U) Immediately prior to loading, the oxidizer containers were propellant passivated. The procedure involved an evacuation to ~ 5 microns, exposure to propellant vapors at 200 mm Hg pressure for 10 minutes, a re-evacuation to ~ 5 microns, re-exposure to propellant vapors at 600 mm Hg pressure for 4 hours, and a third evacuation to ~ 5 microns followed by loading. The fuel containers were not propellant passivated.

(U) All containers were loaded by vacuum transfer from a transfer bomb (containing the required quantity of propellant) to a 2 v/o ullage (at 200 F). (As noted in Fig. 24, the internal volume of all containers, except for those fabricated from 1100 Al, is 595 cc; the 1100 Al bombs have an internal volume of 550 cc.) The amount of propellant loaded was determined gravimetrically during the loading and verified by weight measurements before and after the loading. An argon pad of ~ 1 atm was placed in the containers before sealing (under flowing argon gas) with the Swagelok plugs.

(U) The MHF-5 and MHF-7 containers were loaded on 11 February 1970 and the oxidizer tests were initiated on 23 March 1970. The temperature of the bombs, which are stored in a horizontal position under cover, is allowed to fluctuate with the ambient temperatures (which are recorded) at Rocketdyne's Santa Susana Field Laboratory. During the storage period to date, these temperatures have varied from ~ 40 to 94 F. The tests are being continuously monitored by internal pressure and environmental temperature measurements. At future termination of the tests, the container contents (both liquid and vapor phases) will be chemically analyzed and compared with the initial contents shown in Table 35.

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TABLE 35

PRE-TEST CHEMICAL ANALYSES OF STORABILITY SAMPLES

<u>Chlorine Trifluoride</u>		<u>MHF-5</u>	
ClF_3 , w/o	99.4	$\text{CH}_3\text{N}_2\text{H}_3$, w/o	54.7
HF, w/o	0.3	N_2H_4 , w/o	26.2
FClO_2 , w/o	0.1	$\text{N}_2\text{H}_5\text{NO}_3$, w/o	18.6
ClO_2 , w/o	0.1	$\text{H}_2\text{O} + \text{OSI}$, w/o	0.5
Cl_2 , w/o	0.1		
<u>Chlorine Pentafluoride</u>		<u>MHF-7</u>	
ClF_5 , w/o	98.6	$\text{CH}_3\text{N}_2\text{H}_3$, w/o	80.0
ClF_3 , w/o	1.1	N_2H_4 , w/o	13.5
HF, w/o	0.1	H_2O , w/o	5.9
		OSI, w/o	0.6
<u>Florox</u>			
ClF_3O , w/o	98.7		
ClF_3 , w/o	0.7		
FN_2O_2 , w/o	0.3		
FClO_2 , w/o	0.1		
Cl_2 , w/o	0.1		
HF, w/o	0.1		

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(C) To date, no significant pressure rises have been observed in any of the containers, except in the 321 SS container with MHF-5. The pressure in this container has risen \sim 200 psi over an 8-month period.

Propellant Formulation and Chemical Analyses

(U) All propellants used during the physical and engineering property measurements were of propellant-grade quality obtained from commercial manufacturers or were formulated to specified compositions using standard procedures. The techniques applied in chemical analyses of the propellant samples used in the measurements followed military specification procedures, are equivalent to the specified procedures, or are standard Rocketdyne procedures, which have been developed in the absence of specified procedures. Unless otherwise noted, all propellants used in the measurements were sampled for chemical analysis immediately prior to the indicated measurements. In some of the measurements (i.e., in those cases where the sample quantity was sufficient for analysis), the sample used in the measurements was chemically analyzed after the measurements were completed. During all handling and transfer operations, all required precautions were taken to prevent contamination or chemical change of the propellant sample.

(U) Brief summaries of the procedures used in the formulation of the propellant mixtures and in the chemical analyses of the propellant samples are presented in the following paragraphs. The results of the chemical analyses are presented with the data from the measurements in the appropriate sections.

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(U) IMDFNA. A batch of ~ 900-ml of Inhibited Maximum Density Fuming Nitric Acid (IMDFNA) propellant was formulated from 927.3-g of MIL-P-7254F (Type III LS) nitric acid, 518.3-g of MIL-P-26539C (Type MON-1) nitrogen tetroxide, and 7.0-g of anhydrous HF through use of a vacuum line. Chemical analyses of samples from the HNO_3 and N_2O_4 used in the formulation indicated the following compositions:

<u>N_2O_4</u>	<u>HNO_3</u>
N_2O_4 - 99.00 w/o	HNO_3 - 85.0 w/o
NO - 0.92 w/o	NO_2 - 14.06 w/o
H_2O - 0.04 w/o	H_2O - 0.4 w/o
NOCl - 0.04 w/o	HF - 0.5 w/o
	NVR - 0.04 w/o

(U) The batch of IMDFNA was stored under its own vapor pressure in a 1200-ml 304 SS cylinder. Chemical analyses of two 125-ml samples of this mixture (loaded under vacuum into 150-ml 304 SS cylinders for transfer) indicated the following composition:

HNO_3	- 54.3 w/o
NO_2	- 44.3 w/o
NO	- 0.33 w/o
H_2O	- 0.27 w/o
HF	- 0.8 w/o

(U) Samples of the IMDFNA required for the property measurements described in other sections of this report were withdrawn from the storage cylinder (as required) by a gravimetric volume and vacuum transfer procedure.

(U) The chemical analyses of the nitric acid and nitrogen tetroxide ingredients were conducted with the procedures given in specifications MIL-P-7254E and MIL-P-26539C, respectively. The formulated composition was determined synthetically from calculations of the ingredient quantities and experimental confirmation (by chemical analyses) of the total acid, HF, and NO_2 concentrations using the procedures of MIL-P-7254E and of the NO concentration using the procedure described in MIL-P-26539C.

(U) Nitrogen Tetroxide. The nitrogen tetroxide (N_2O_4) was obtained commercially and chemically analyzed using the procedures specified in MIL-P-26539C.

(U) MON-10. The MON-10 (90 w/o N_2O_4 - 10 w/o NO) samples used in the measurements were from a 2-lb batch supplied by the Air Force Rocket Propulsion Laboratory. The chemical analysis was conducted using the techniques described in MIL-P-27408A (proposed).

(U) Chlorine Trifluoride. The chlorine trifluoride (ClF_3) was obtained from a commercial source and chemically analyzed using procedures similar to those specified in MIL-P-81399A.

(U) Chlorine Pentafluoride. The chlorine pentafluoride (ClF_5) used in the program was obtained from a batch produced at Rocketdyne's production facility. Samples were chemically analyzed by procedures similar to those specified in MIL-P-27413.

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(C) Florox. Florox (ClF_3O) was obtained from a batch of propellant produced at Rocketdyne under Contract N00019-68-C-0332 (Ref. 7) and transferred by the Navy to AFRPL. Chemical analyses of the ClF_3O samples were conducted with procedures similar to those employed on ClF_3 and ClF_5 . Gas chromatography (with a shorter version of the same column used in ClF_5 analyses) was used to determine all concentrations except for HF, which was determined by infrared spectrophotometry.

(C) MOR-5. The MOR-5 (nominal composition: 78 w/o ClF_3O - 22 w/o ClF_5) samples were formulated from the ingredients by mixing the appropriate quantities through use of a vacuum line. Gas chromatography was used to determine the impurities, while infrared spectrophotometry was used to determine ClF_5 concentration. The ClF_3O concentration was determined by difference.

(U) Hydrazines. The various hydrazine propellants, i.e., N_2H_4 , $\text{CH}_3\text{N}_2\text{H}_3$, $(\text{CH}_3)_2\text{N}_2\text{H}_2$, and the 50 w/o N_2H_4 - 50 w/o $(\text{CH}_3)_2\text{N}_2\text{H}_2$ blend, were obtained from typical commercial sources. Chemical analyses of the samples used in the experimental measurements were conducted using gas chromatography techniques similar to those specified in MIL-P-26536C (N_2H_4), MIL-P-27464A ($\text{CH}_3\text{N}_2\text{H}_3$), MIL-P-25604D $[(\text{CH}_3)_2\text{N}_2\text{H}_2]$, and MIL-P-27402B $[50 \text{ w/o } \text{N}_2\text{H}_4 - 50 \text{ w/o } (\text{CH}_3)_2\text{N}_2\text{H}_2]$.

(C) MHF-3. The MHF-3 (nominal composition: 86 w/o $\text{CH}_3\text{N}_2\text{H}_3$ - 14 w/o N_2H_4) samples were formulated from appropriate quantities of N_2H_4 and $\text{CH}_3\text{N}_2\text{H}_3$ in an inert gas glove box. Chemical analysis of each sample was determined by a combination of gas chromatography and the total

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(c) hydrazines assay value as established by Redox titrimetry using the primary standard KIO_3 ; impurity concentrations were determined by direct gas chromatography.

(c) MHF-5. The MHF-5 (nominal composition: 55 w/o $\text{CH}_3\text{N}_2\text{H}_3$ - 26 w/o N_2H_4 - 19 w/o $\text{N}_2\text{H}_5\text{NO}_3$) samples were formulated in a Rocketdyne production facility by the addition of NH_4NO_3 to a large excess of $\text{CH}_3\text{N}_2\text{H}_3$:



The NH_3 was removed by purging dry GN_2 through the mixture. The final step involved addition of the additional $\text{CH}_3\text{N}_2\text{H}_3$ and N_2H_4 required to provide the desired concentration; the ingredients were then stirred until the blend was homogeneous. In chemical analyses of the samples, $\text{CH}_3\text{N}_2\text{H}_3$ and N_2H_4 concentrations were determined by a combination of Redox titrimetry and gas chromatography, following sample treatment with sodium methoxide. The nitrate concentrations were determined by non-aqueous titration, and H_2O and NH_3 were determined by direct gas chromatography.

(u) MHF-7. The MHF-7 formulations used in the experimental measurements were blended from appropriate quantities of propellant-grade $\text{CH}_3\text{N}_2\text{H}_3$ and N_2H_4 , and deionized water. Six different formulations were prepared to yield a series of solutions in which the component compositions varied by about 5 w/o from the nominal values. Chemical analyses of the formulations indicated the following compositions:

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MHF-7 Formulation	Composition			
	$\text{CH}_3\text{N}_2\text{H}_3$, w/o	N_2H_4 , w/o	H_2O , w/o	OSI, w/o
-N (nominal)	81.3	14.2	4.2	0.3
-1	75.9	14.5	9.3	0.3
-2	76.2	19.1	4.4	0.3
-3	81.2	8.8	9.5	0.5
-4	86.5	8.9	4.3	0.3
-5	80.7	18.7	0.3	0.3

The chemical analyses were conducted using the same technique described for chemical analysis of MHF-3.

(U) $\text{N}_2\text{H}_4\text{-N}_2\text{H}_5\text{N}_3$. The monopropellant formulation of 77 w/o N_2H_4 - 23 w/o $\text{N}_2\text{H}_5\text{N}_3$ was prepared by adding NH_4N_3 to propellant-grade N_2H_4 in the proper ratio to form the indicated composition after the evolved NH_3 was removed. The N_2H_4 was chemically analyzed as 99.0 w/o N_2H_4 - 0.6 w/o H_2O - 0.4 w/o aniline and the NH_4N_3 was prepared by reacting $(\text{NH}_4)_2\text{SO}_4$ with NaH_3 . The last traces of NH_3 were removed from the primary formulation by outgassing the mixture at 40 F. No chemical analyses were conducted on the final formulation.

PHASE III: EVALUATION AND COMPILEDATION OF DATA

OBJECTIVE

(U) During the entire period of the contracted program, efforts under Phase III were directed toward the assembly of all data generated by Phases I and II, unification of the data sources, critical comparison of conflicting data, and tabulation of the results.

RESULTS AND ACCOMPLISHMENTS

(U) Phase III effort during the program included the compilation and evaluation of physical properties data of selected propellants and an assembly of a bibliography on ClF₅/ and ClF₃/material interactions from the references located in the Phase I literature survey. The remaining work in the phase was related to the reduction, evaluation, and correlation of all data generated from the Phase II experimental efforts. However, to maintain continuity in this text, the latter results are reported under the pertinent Phase II headings.

Physical Properties Data Sheets

(U) As noted in Phase I, a comprehensive search of the propellant properties literature was conducted to locate all pertinent physical properties data for monomethylhydrazine (CH₃N₂H₃), cyanogen (C₂N₂), the mixed oxides of nitrogen (N₂O₄-NO mixtures) and the fuming nitric acids. The data obtained from this search were critically evaluated and correlated under Phase III; the resulting data sheets, presented in both metric and English units, are given as Appendices A, B, C, and D, respectively. When agreement among various sets of experimental data for the individual

propellants was good and when sufficient data were available, these data were combined and correlated with a least-squares curve-fit computer program. The resulting equations are included with the graphical representations of the data. These sheets represent Rocketdyne's recommendations of the best-value physical properties data for $\text{CH}_3\text{N}_2\text{H}_3$, C_2N_2 , the mixed oxides of nitrogen, and the fuming nitric acids.

- (U) Because of the extensive Phase II experimental efforts directed at Florox, MOR-5, and MHF-7, physical property data sheets were also assembled for these propellants. Although these data sheets (presented in Appendices E, F, and G, respectively) are primarily compilations of the data resulting from Phase II efforts, some additional data from other Rocketdyne studies on these propellants are included and referenced.
- (U) Monomethylhydrazine. The physical and thermodynamic properties of monomethylhydrazine are given in Appendix A. Experimental data are used when available; calculated data are referenced as such. Values for the isothermal compressibility of liquid MMH were calculated by the method of Lyderson, Greenkorn, and Hougen (Ref. 19) after a careful study of the available correlation techniques.
- (U) Cyanogen. All available physical and thermodynamic data for cyanogen have been summarized in Appendix B. Because of the small liquidus range of this compound, only limited data are available for some of the properties (e.g., heat capacity, viscosity, etc.).

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(U) Mixed Oxides of Nitrogen (MON). Various physical properties of N_2O_4 -NO mixtures (over the composition range of propellant interest) are presented in Appendix C. The evaluation of the experimental data was extremely difficult because of large disagreements among the various sets of measurements and the questionable accuracy of the results. The curve-fit equations given in Appendix C, therefore, are Rocketdyne's recommendations for the best representation of the available data for the compositions of interest. It should be noted that comparison of Rocketdyne's previous evaluation of pure nitrogen tetroxide properties (Ref. 2) with the current MON evaluation will reveal certain discrepancies. This, in part, is attributed to the fact that the data for pure nitrogen tetroxide was not included in the MON evaluation. It should also be emphasized that the chemistry of the N_2O_4 -NO system is extremely complicated, and further characterization (or confirmation) of desired MON properties is recommended.

(U) Fuming Nitric Acids. During the program, a compilation and evaluation of the physical properties data for the fuming nitric acids were initiated. Evaluations were completed on the densities, vapor pressures, and viscosities of WFNA, RFNA, and MDFNA as a function of temperature and composition. These evaluations are summarized in Appendix D.

(C) Florox. The physical properties data sheets on MOR-5 (nominal composition: 78 w/o ClF_3O - 22 w/o ClF_5) are presented with attendant figures as Appendix F.

(C) MOR-5. The physical properties data sheets on MOR-5 (nominal composition: 78 w/o ClF_3O - 22 w/o ClF_5) are presented with attendant figures as Appendix F.

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- (U) MHF-7. Appendix G contains the summation of the physical properties of MHF-7. In addition to the correlations of the Phase II experimental data on the saturated liquid as functions of temperature and composition, the MHF-7 data sheets contain extrapolations of the data on the nominal formulation to temperatures of ~ 300 F and pressures of 2000 psia. The temperature limit of ~ 300 F (~ 150 C) was selected arbitrarily as the level at which decomposition of the propellant might be initiated with resultant unpredictable effects on the propellant properties. The techniques used to extrapolate the experimental data are briefly described as follows.
- (U) The pseudocritical temperature was estimated with Kay's Method (Ref. 20). Three estimation methods for the pseudocritical pressure gave almost identical results: Kay's Method (Ref. 20), the modified Prausnitz and Gunn technique (Ref. 21), and extrapolation of the experimental vapor pressure curve to the pseudocritical temperature (employing a Duhring plot with $\text{CH}_3\text{N}_2\text{H}_3$ as the reference substance). The pseudocritical compressibility factor was estimated with the Garcia-Barcena boiling-point correlation (Ref. 22). The pseudocritical density and specific volume were then calculated from the previously estimated values for pseudocritical temperature, pressure, and compressibility factor.
- (U) The density data were extrapolated by using the Lydersen, Greenkorn, and Hougen corresponding-state correlation (Ref. 19). The heat capacity data were extrapolated through use of the Watson expansion factor technique (Ref. 23) and a reduced-state correlation. The viscosity data were extrapolated to higher temperatures with the Guzman-Andrade equation (Ref. 24) and to higher pressures with a reduced-state correlation based on the water correlation of Theiss (Ref. 25). None of the available

estimation techniques were satisfactory in extrapolating the thermal conductivity data to higher temperatures; therefore, the small extrapolation shown in the graphs was made graphically. The thermal conductivity values at higher pressures were estimated from the corresponding values for saturated liquid by using Lenoir's correlation (Ref. 26).

- (U) The extrapolated and calculated data are noted in the tables and are represented in the figures with a dashed line.

ClF₅/ and ClF₃/Materials Interactions Bibliography

- (U) A bibliography of pertinent reports describing studies directed at, or evolving from, the characterization of materials interactions with ClF₅ and ClF₃ was compiled. This bibliography has been assembled in Appendix H.

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APPENDIX A

PHYSICAL PROPERTIES OF MONOMETHYLHYDRAZINE

(U) The physical and thermodynamic properties of monomethylhydrazine are presented in Tables A-1 through A-3. Figures A-1 through A-10a are graphical illustrations of the properties listed in Table A-1.

TABLE A-1

PHYSICAL PROPERTIES OF MONOMETHYLHYDRAZINE AT 25 C (77 F)

Property	Value		Figure Number	Reference Number
	Metric	English		
General Identification				
Identification		Monomethylhydrazine, MMH		
Molecular Formula	$\text{CH}_3\text{N}_2\text{H}_3$			
Molecular Weight	46.072			
Freezing Point	-52.37 C	-62.27 F		A-1
Triple Point	—	—		A-2
Normal Boiling Point	87.95 C*	190.3 F*		A-2, -3
Critical Properties				
Temperature	312 C	593.6 F		A-3
Pressure	81.3 atm	1195 psia		A-3
Density	0.29 g/ml	18.1 lb/cu ft		A-3
Phase Properties				
Density	0.8711 g/cc	54.386 lb/cu ft	A-1, -1a	A-3, -4
Solid				
Liquid				
Gas	$1.062 \times 10^{-3}/\text{C}^{**}$	$5.90 \times 10^{-4}/\text{F}^{**}$		—
Thermal Expansion	$\left(\frac{1}{V} \left(\frac{\partial V}{\partial T}\right)_P\right)$			
Compressibility	$4.846 \times 10^{-5} \text{ atm}^{-1}$	$3.297 \times 10^{-6} \text{ psi}^{-1}$	A-2, -2a	A-5
Adiabatic	$3.90 \times 10^{-5} \text{ atm}^{-1}^{**}$	$2.65 \times 10^{-6} \text{ psi}^{-1}^{**}$	A-6	A-6
Isothermal	0.065 atm	0.955 psia	A-3, -3a	A-2, -3
Vapor Pressure				

*Calculated from vapor pressure equation

**Calculated data

TABLE A-1
(Continued)

PHYSICAL PROPERTIES OF MONOMETHYLDIAZINE AT 25 °C (77 °F)

Property	Value	Figure Number	Reference Number
	Metric	English	
<u>Phase Properties (Continued)</u>			
Surface Tension	53.82 dynes/cm	2.317×10^{-3} lb/ft	A-4, -4a
<u>Thermodynamic Properties</u>			
Heats of			
Formation (Liquid)	+12.95 Kcal/mole	+505.9 Btu/lb	A-7
Fusion	2490.5 cal/mole at MP	97.30 Btu/lb at MP	A-2
Vaporization	9648 cal/mole	376.9 Btu/lb	A-2
Combustion (Gross)	311.711 kcal/mole	12178.3 Btu/lb	A-8
Heat Capacity			
Solid	0.3893 cal/g-C at MP	0.3893 Btu/lb-F at MP	A-5, -5a Table A-2
Liquid	0.700 cal/g-C	0.700 Btu/lb-F	A-6, -6a Table A-2
Gas	—	—	Table A-3 A-2
Cp	—	—	A-7, Tables A-2 and -3
Cv	—	—	A-7, Tables A-2 and -3
Entropy	—	—	
Enthalpy	—	—	
<u>Transport Properties</u>			
Viscosity	5.21 $\times 10^{-4}$ lb _m /ft-sec	A-8, -8a	A-3, -11
Liquid	0.776 centipoise		
Gas			

TABLE A-1

(Concluded)

PHYSICAL PROPERTIES OF MONOMETHYLDIAZINE AT 25 C (77 F)

Property	Value		Figure Number	Reference Number
	Metric	English		
Transport Properties (Continued)				
Thermal Conductivity				
Liquid	5.903×10^{-4} cal/cm-sec-c	0.1428 Btu/hr-ft-F	A-9, -9a	A-9
Gas				
Sonic Velocity				
Liquid	1548.9 m/sec			
Gas		5631.8 ft/sec	A-10, -10a	A-5
Electromagnetic Properties				
Index of Refraction				
Dipole Moment	1.68 \pm 0.14 Debyes			A-12
Dielectric Constant				
Liquid		$\begin{cases} 19.2 & \text{at } 15.6 \text{ C (60 F)} \\ 17.3 & \text{at } 32.2 \text{ C (90 F)} \end{cases}$		A-13
Gas				
Electrical Conductivity		$4.1 \times 10^{-5} \text{ ohm}^{-1} \text{ cm}^{-1}$ at 23 C (73.4 F)		A-14
Magnetic Susceptibility				
			<u>General Description</u>	

Appearance: Clear, colorless, hygroscopic liquid
Odor: Ammoniacal odor characteristic of relatively low molecular weight amines

Toxicity: Threshold Limit Value (TLV) = 0.5 ppm
Composition: Military Specification MIL-P-27404

Monomethylhydrazine Assay 98.0 w/o min.
H₂O Plus Other Soluble Impurities 2.0 w/o max.
Melting Point -67.9 F max.
Density at 77 F 0.872 \pm 0.002 g/ml
Transmittancy 90 Percent min.

TABLE A-2

THERMODYNAMIC PROPERTIES OF SOLID AND
LIQUID MONOMETHYLHYDRAZINE (Ref. A-2, -9)

Temperature		Heat Capacity		Entropy		Enthalpy ($H_T - H_{298(g)}$)	
K	R	cal/mole-K	Btu/1b-R	cal/mole-K	Btu/1b-R	Kcal/mole	Btu/1b
0	0	0	0	0	0	-2.218	-86.66
40	72	3.930	0.0853	1.791	0.0389	-2.140	-83.61
50	90	5.229	0.1135	2.813	0.0611	-2.094	-81.81
60	108	6.409	0.1391	3.874	0.0841	-2.036	-79.55
70	126	7.482	0.1624	4.944	0.1073	-1.966	-76.81
80	144	8.463	0.1837	6.009	0.1304	-1.887	-73.73
90	162	9.357	0.2031	7.058	0.1532	-1.798	-70.25
100	180	10.173	0.2208	8.087	0.1755	-1.700	-66.42
110	198	10.928	0.2372	9.093	0.1974	-1.594	-62.28
120	216	11.624	0.2523	10.074	0.2187	-1.482	-57.90
130	234	12.278	0.2665	11.030	0.2394	-1.362	-53.21
140	252	12.900	0.2800	11.963	0.2597	-1.236	-48.29
150	270	13.499	0.2930	12.874	0.2794	-1.104	-43.13
160	288	14.080	0.3056	13.754	0.2987	-0.966	-37.74
170	306	14.660	0.3182	14.635	0.3177	-0.823	-32.15
180	324	15.250	0.3310	15.490	0.3362	-0.673	-26.29
190	342	15.853	0.3441	16.331	0.3545	-0.518	-20.24
200	360	16.485	0.3578	17.160	0.3725	-0.356	-13.91
210	378	17.157	0.3724	17.981	0.3903	-0.188	-7.35
220	396	17.876	0.3880	18.796	0.4080	-0.013	-0.51
220.79	397.42	17.936	0.3893	18.860	0.4094	0.002	+0.08
<hr/>							
220.79	397.42	31.380	0.6811	30.140	0.6542	2.492	97.36
223.15	401.7	31.384	0.6812	30.474	0.6614	2.566	100.25
233.15	419.7	31.416	0.6819	31.850	0.6913	2.880	112.52
243.15	437.7	31.481	0.6833	33.171	0.7200	3.195	124.83
253.15	455.7	31.578	0.6854	34.442	0.7476	3.510	137.14
263.15	473.7	31.698	0.6880	35.667	0.7742	3.826	149.48
273.15	491.7	31.836	0.6910	36.852	0.7999	4.144	161.91
283.15	509.7	31.997	0.6945	38.000	0.8248	4.463	174.37
293.15	527.7	32.167	0.6982	39.113	0.8489	4.784	186.91
303.15	545.7	32.352	0.7022	40.195	0.8724	5.107	199.53
313.15	563.7	32.541	0.7063	41.248	0.8953	5.431	212.19
323.15	581.7	32.730	0.7104	42.274	0.9176	5.757	224.93
333.15	599.7	32.923	0.7146	43.274	0.9393	6.086	237.78
343.15	617.7	33.107	0.7186	44.251	0.9605	6.416	250.67
353.15	635.7	33.287	0.7225	45.204	0.9811	6.748	263.64
363.15	653.7	33.453	0.7261	46.136	1.001	7.081	276.65
373.15	671.7	33.600	0.7293	47.047	1.021	7.417	289.78
383.15	689.7	33.734	0.7322	47.937	1.040	7.753	302.91
393.15	707.7	33.840	0.7345	48.808	1.059	8.091	316.12

TABLE A-3
THERMODYNAMIC PROPERTIES OF MONOMETHYLHYDRAZINE
(IDEAL GAS) (Ref. A-2)

Temperature		Heat Capacity		Entropy		Enthalpy ($H_T - H_{298}$)	
K	R	cal/mole-K	Btu/lb-R	cal/mole-K	Btu/lb-R	cal/mole	Btu/lb
298.16	536.7	17.0	0.369	66.61	1.445	0	0
300	540	17.11	0.371	66.72	1.448	31	0.67
400	720	21.0	0.456	72.20	1.567	1,944	42.18
500	900	24.3	0.527	77.29	1.677	4,220	91.57
600	1080	27.1	0.588	81.93	1.778	6,792	147.4
700	1260	29.3	0.636	86.30	1.873	9,602	208.4
800	1440	31.3	0.679	90.33	1.960	12,642	274.3
900	1620	33.1	0.718	94.02	2.040	15,852	344.0
1000	1800	34.6	0.751	97.63	2.119	19,192	416.5
1200	2160	37.1	0.805	104.18	2.261	26,392	572.7
1500	2700	39.8	0.864	112.90	2.450	37,982	824.2

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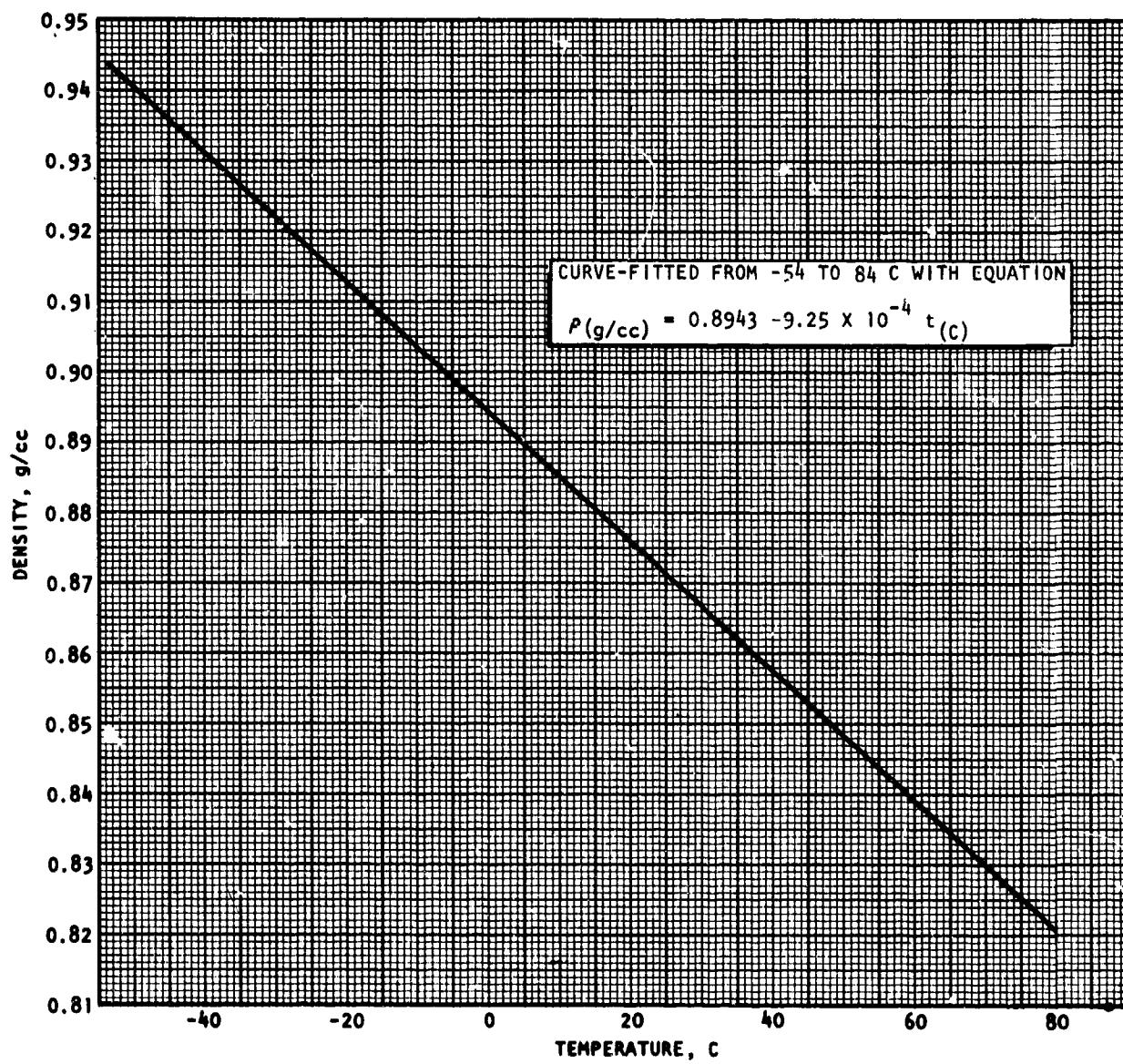


Figure A-1. Density of Liquid Monomethylhydrazine (Ref. A-3 and A-4)

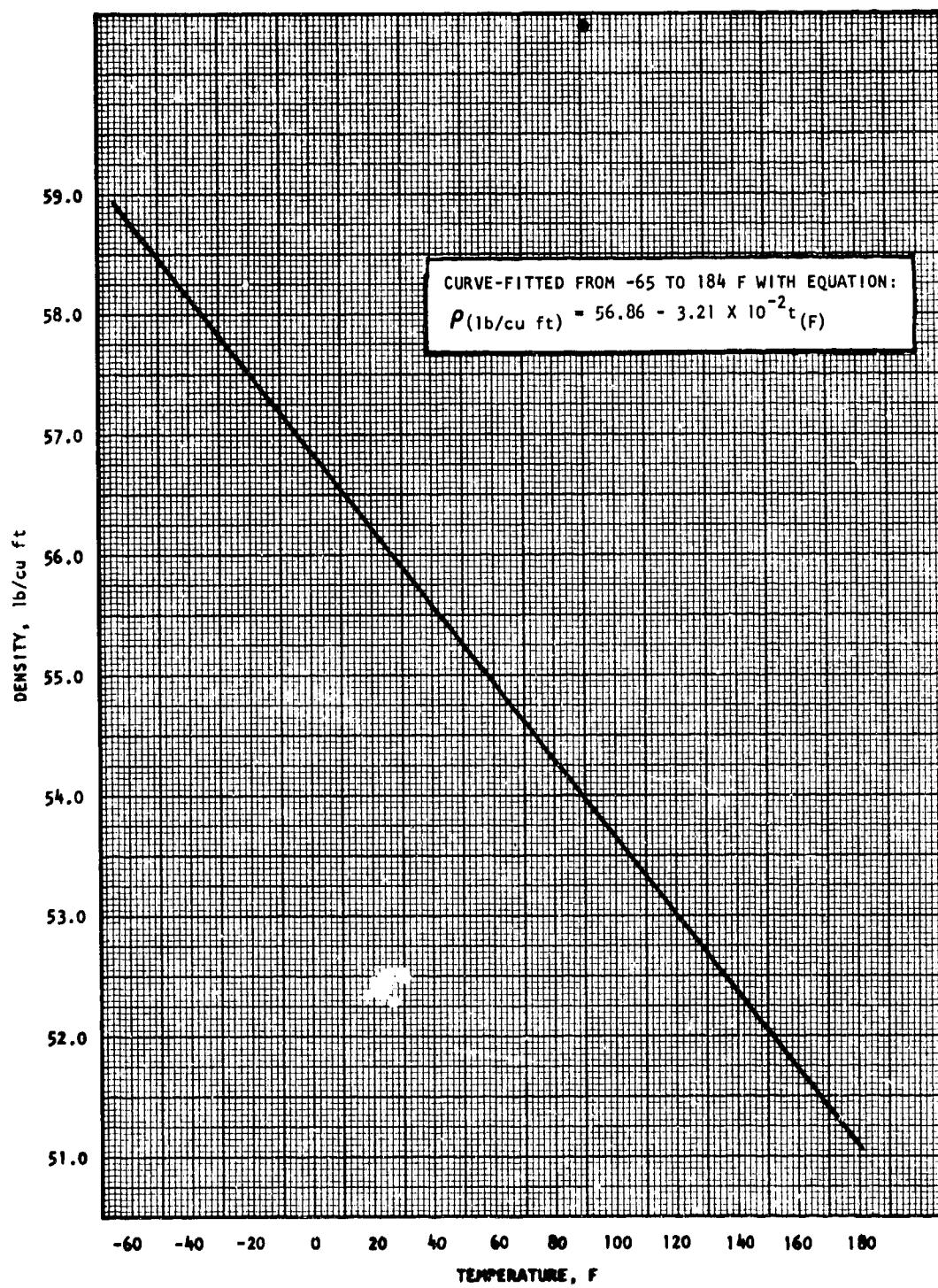


Figure A-1a. Density of Liquid Monomethylhydrazine (Ref. A-3 and A-4)

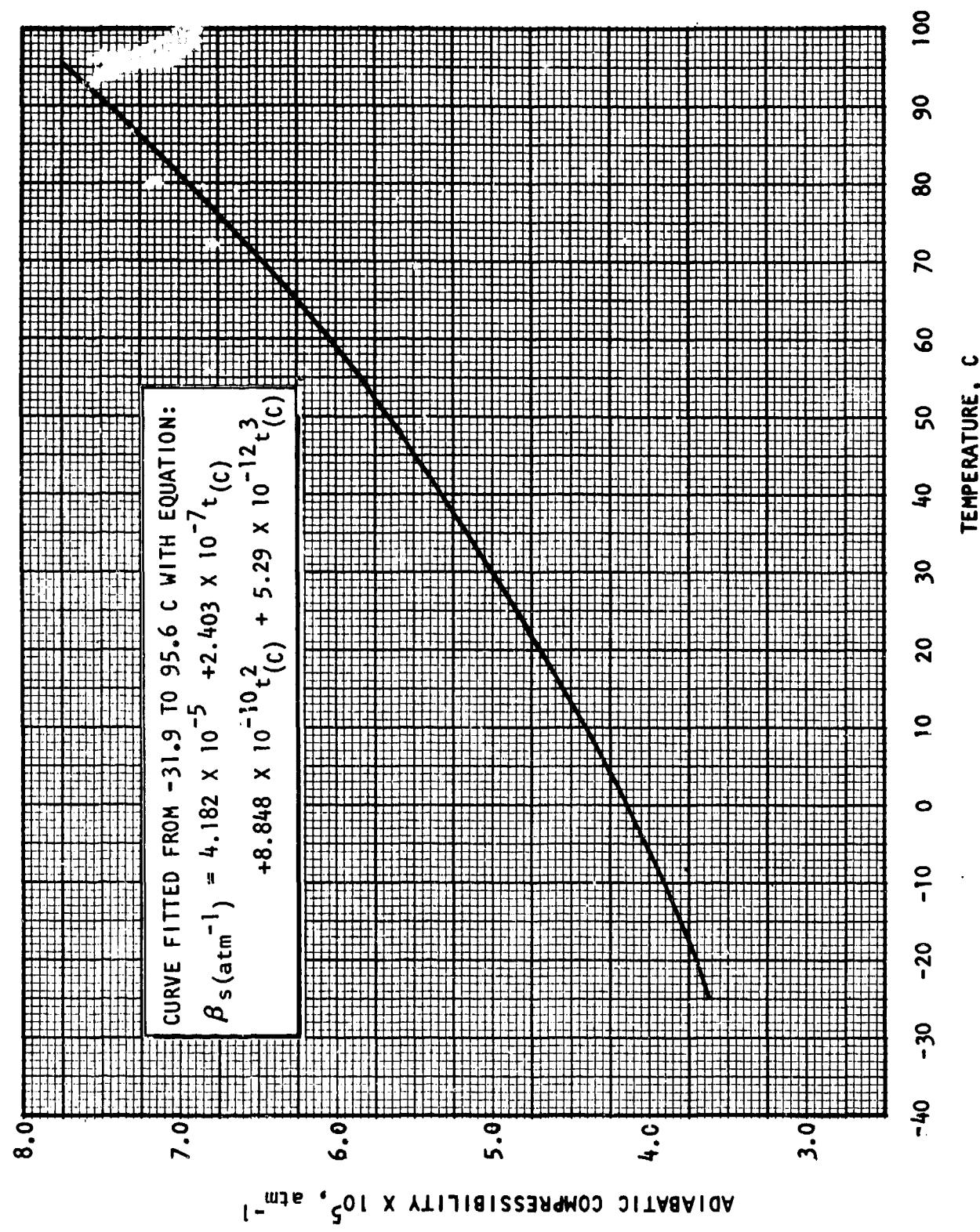


Figure A-2. Adiabatic Compressibility of Liquid Monomethylhydrazine (Ref. A-5)

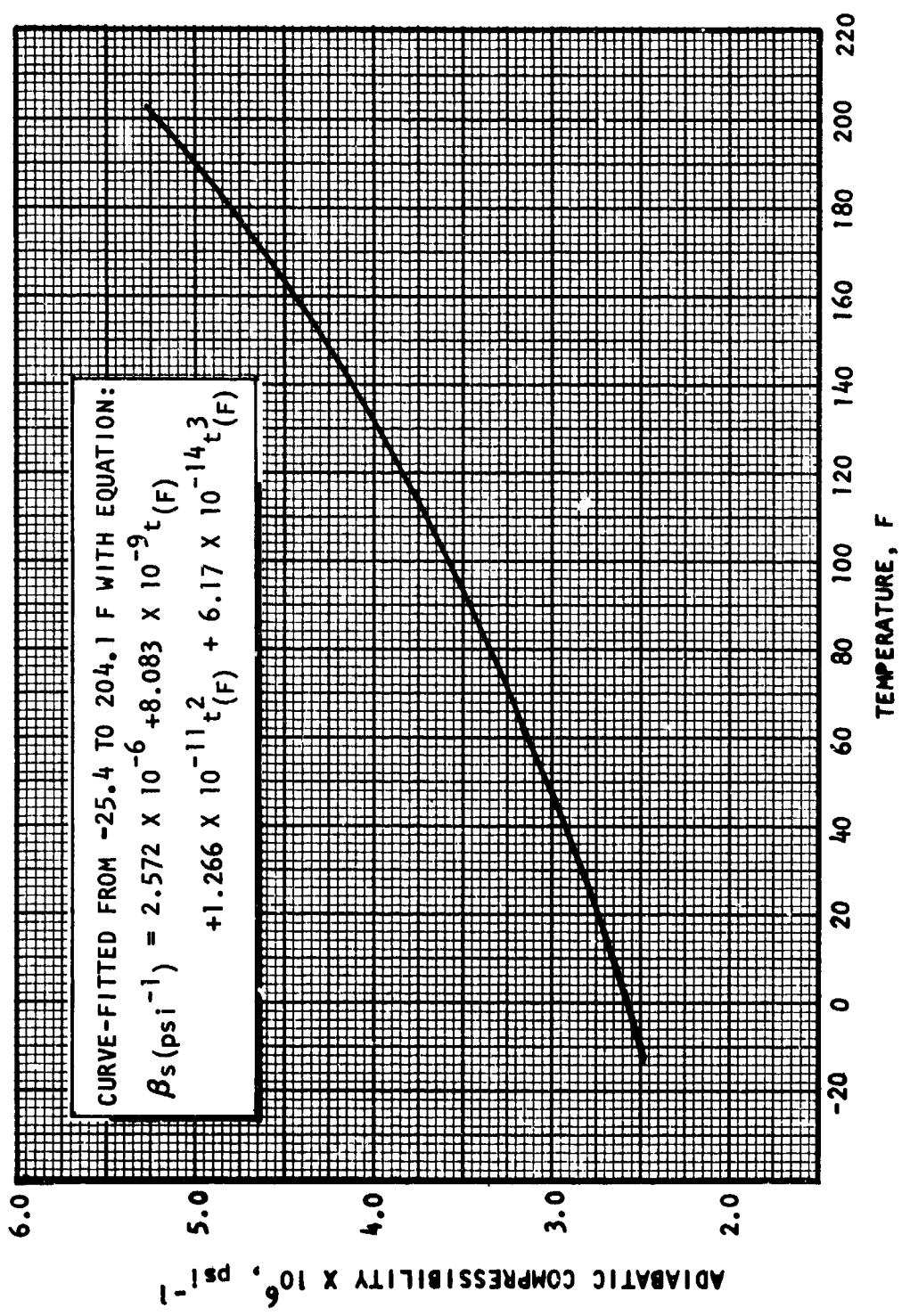


Figure A-2a. Adiabatic Compressibility of Liquid Monomethylhydrazine (Ref. A-5)

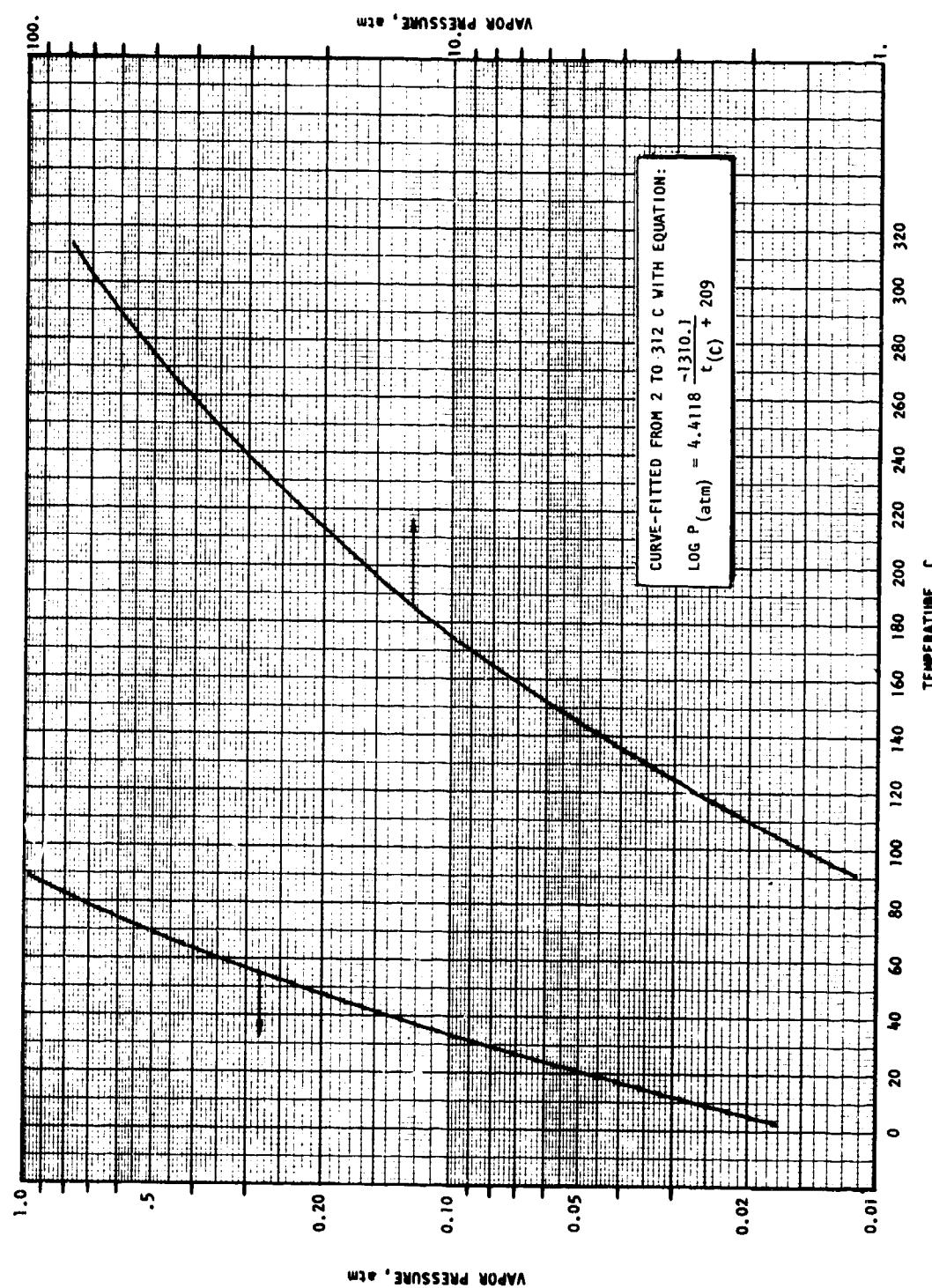


Figure A-3. Vapor Pressure of Monomethylhydrazine (Ref. A-2 and A-3)

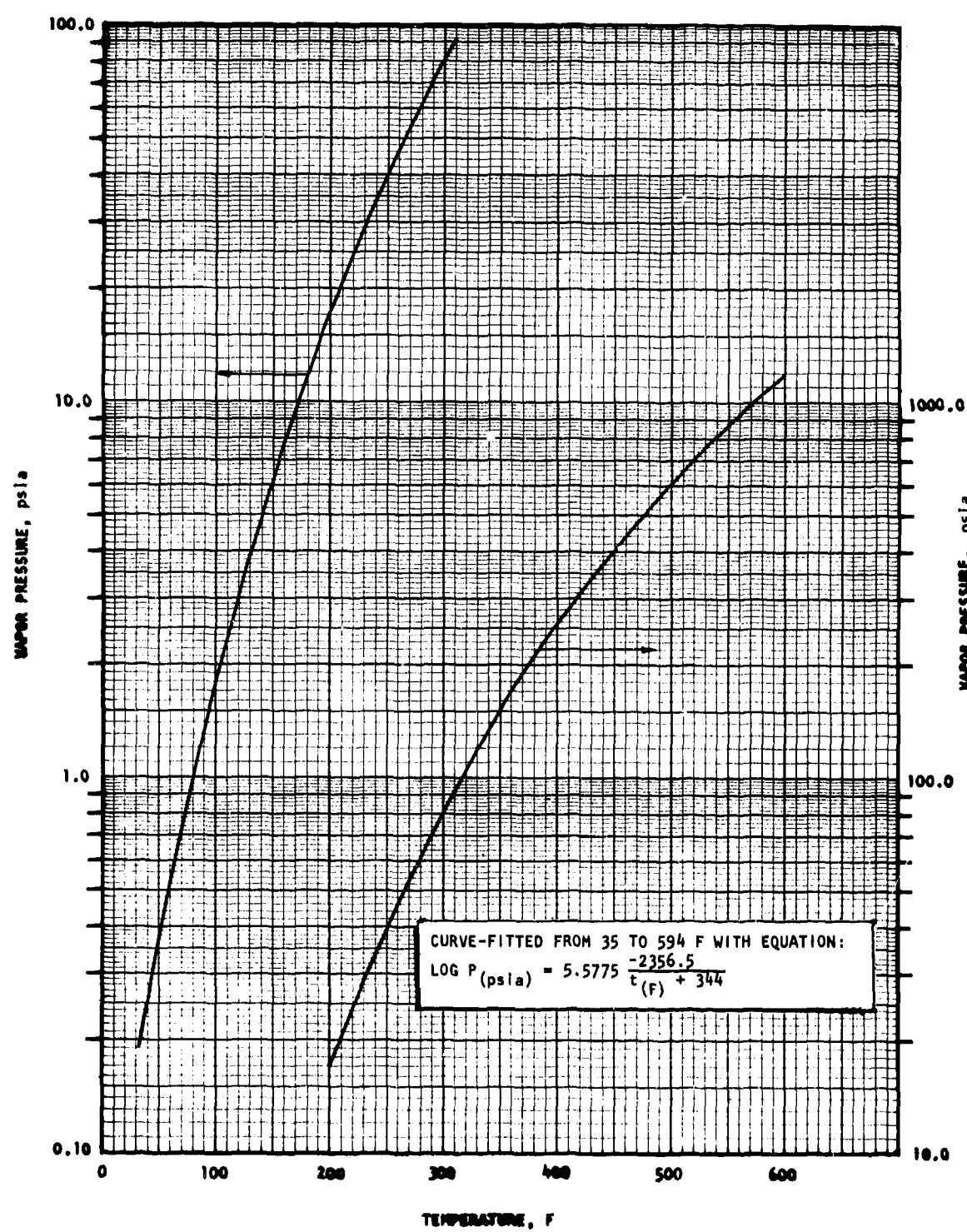
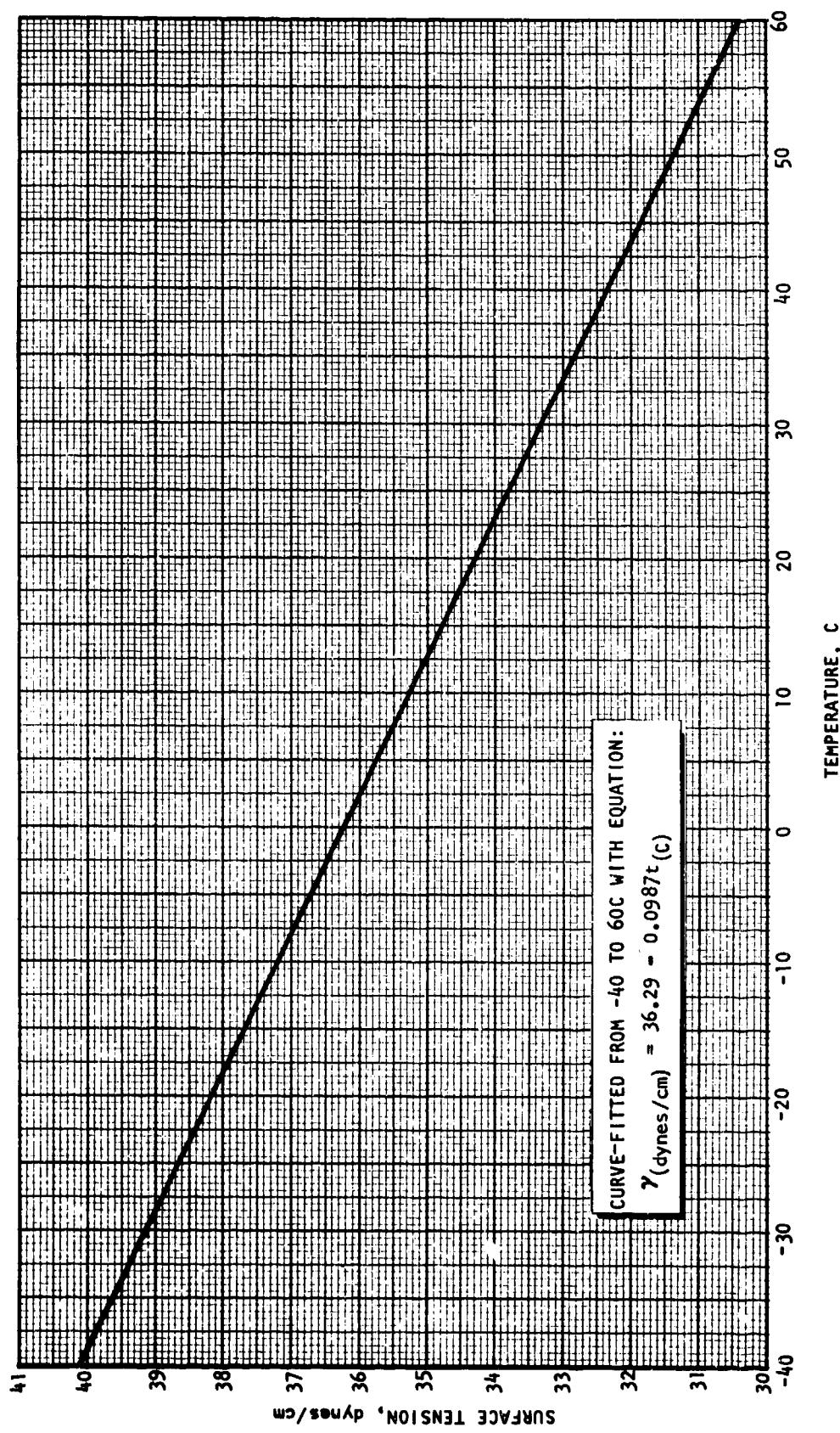


Figure A-3a. Vapor Pressure of Monomethylhydrazine (Ref. A-2 and A-3)



A-15

Figure A-4. Surface Tension of Monomethylhydrazine (Ref. A-3)

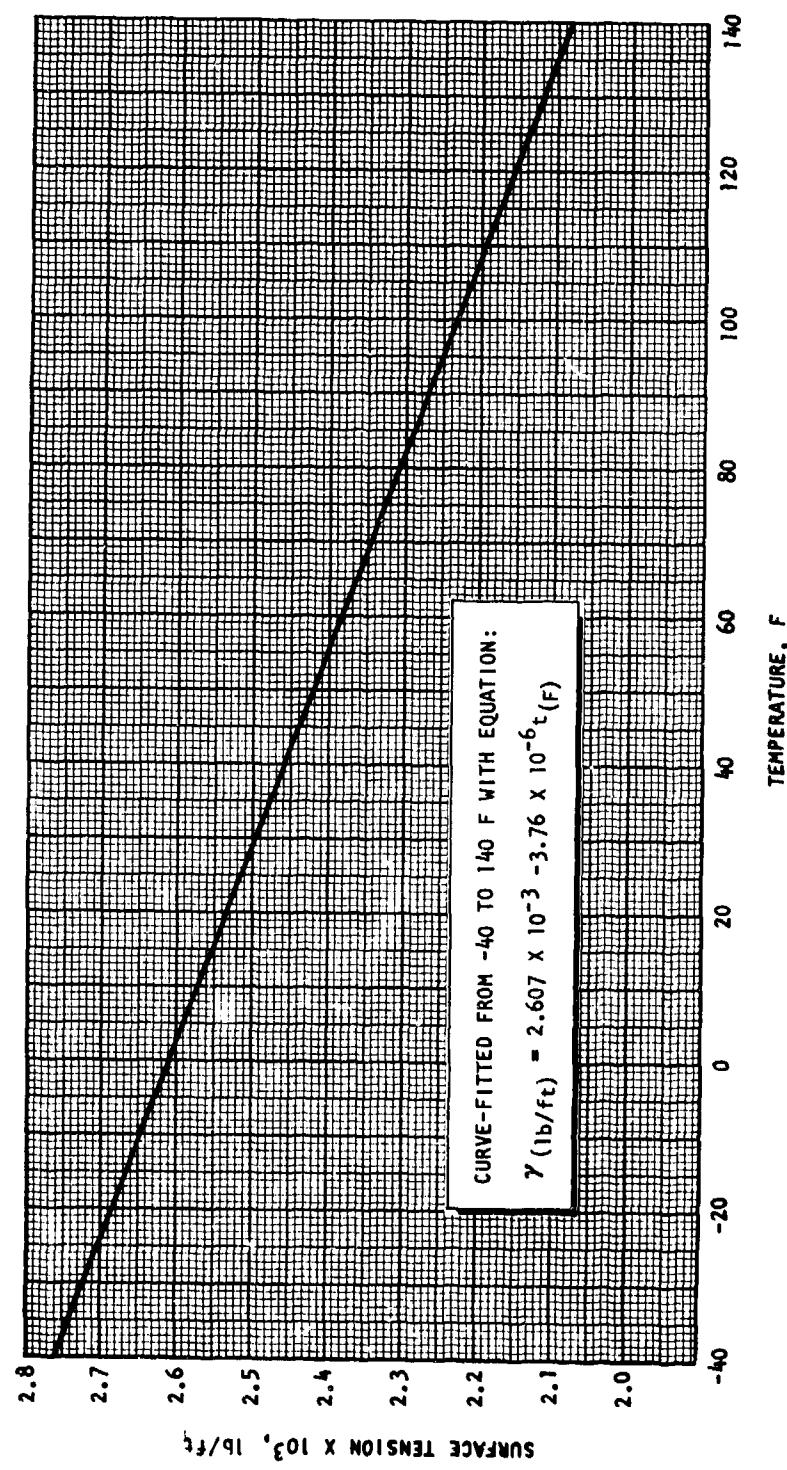


Figure A-4a. Surface Tension of Monomethylhydrazine (Ref. A-3)

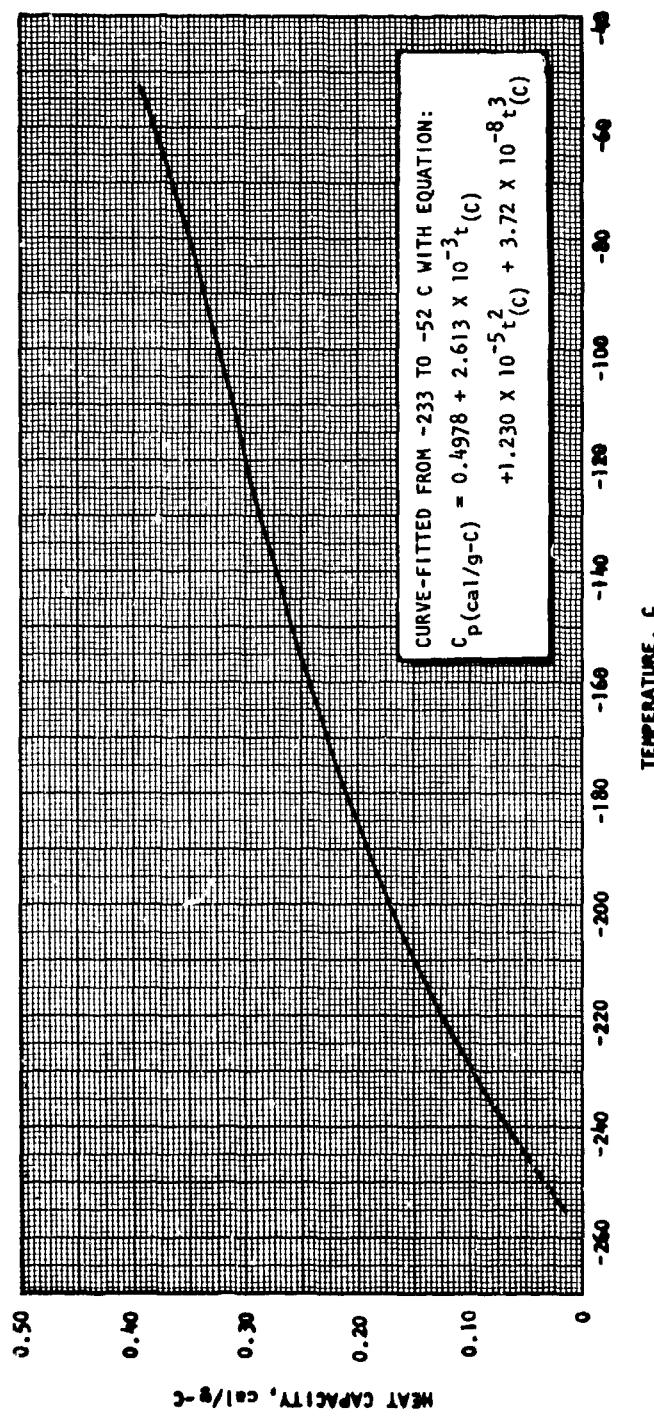


Figure A-5. Heat Capacity of Solid Monomethylhydrazine (Ref. A-2)

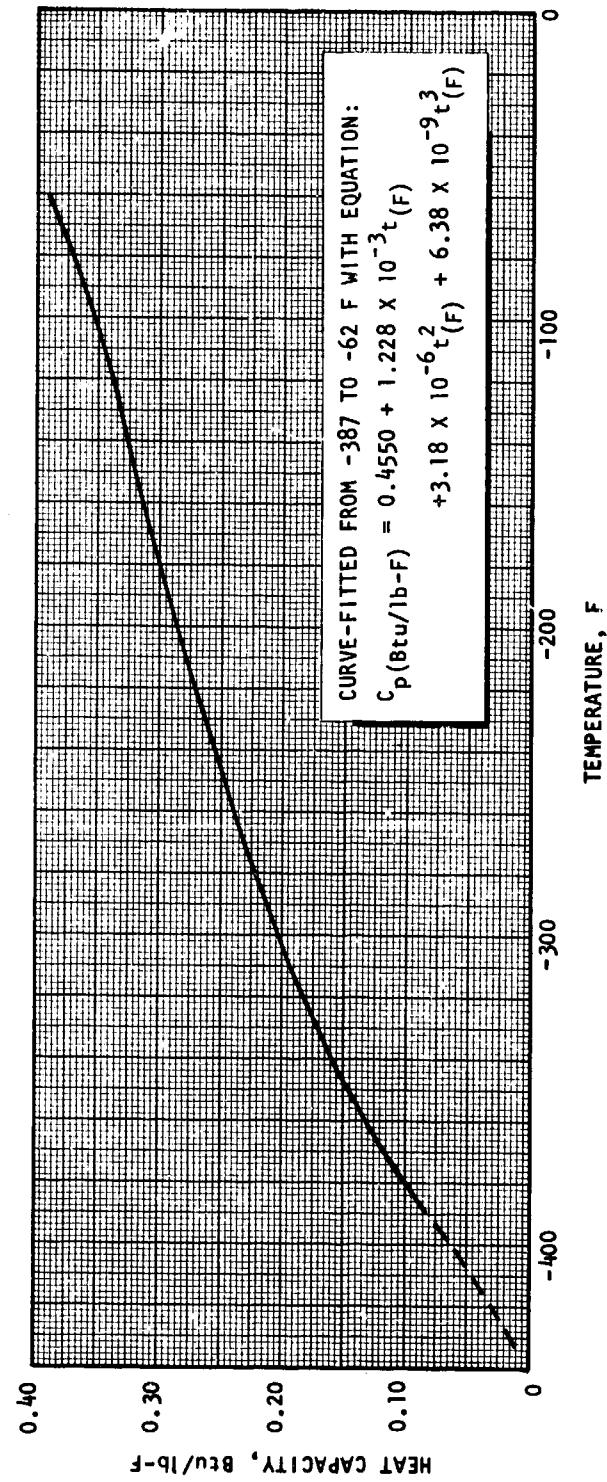


Figure A-5a. Heat Capacity of Solid Monomethylhydrazine (Ref. A-2)

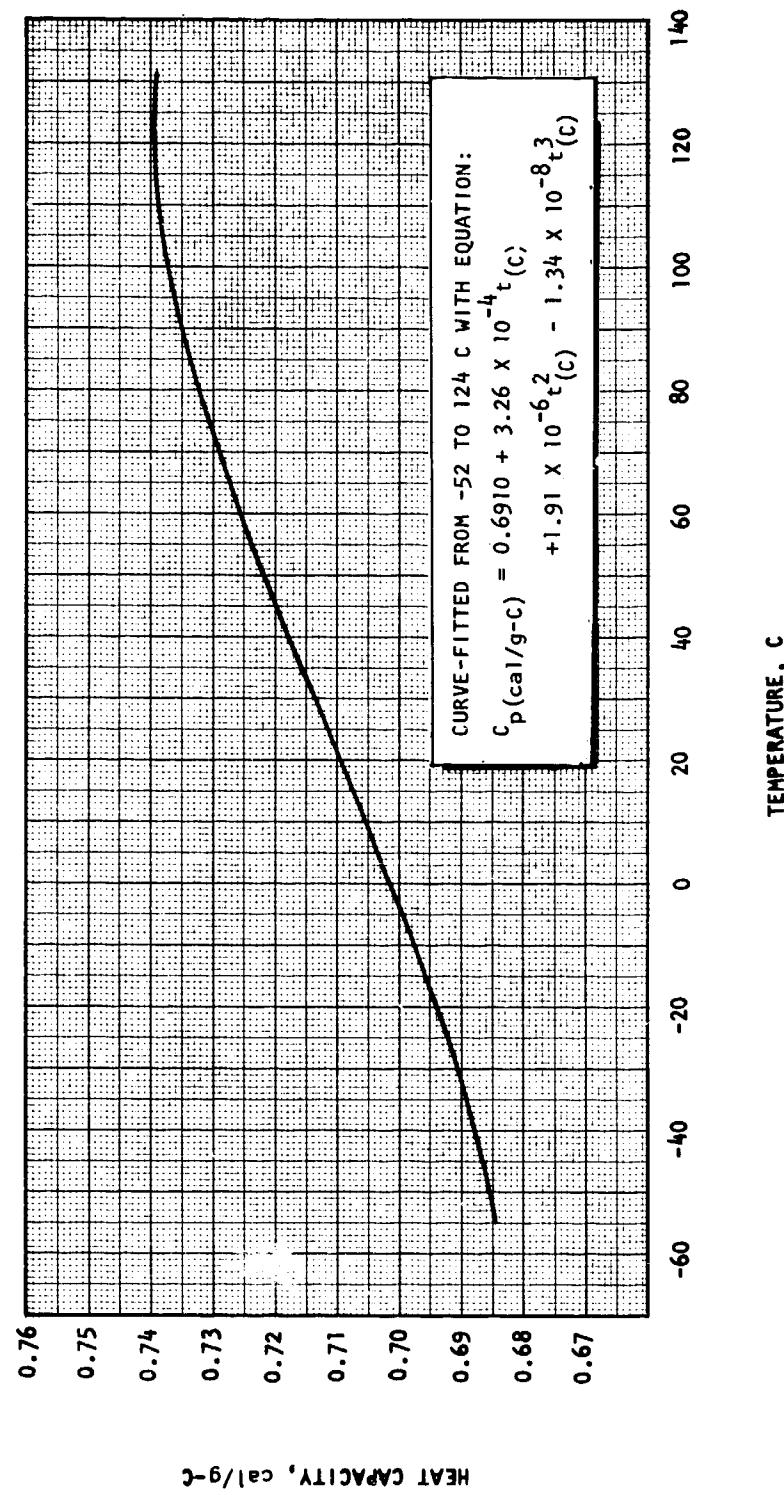


Figure A-6. Heat Capacity of Liquid Monomethylhydrazine (Ref. A-2 and A-9)

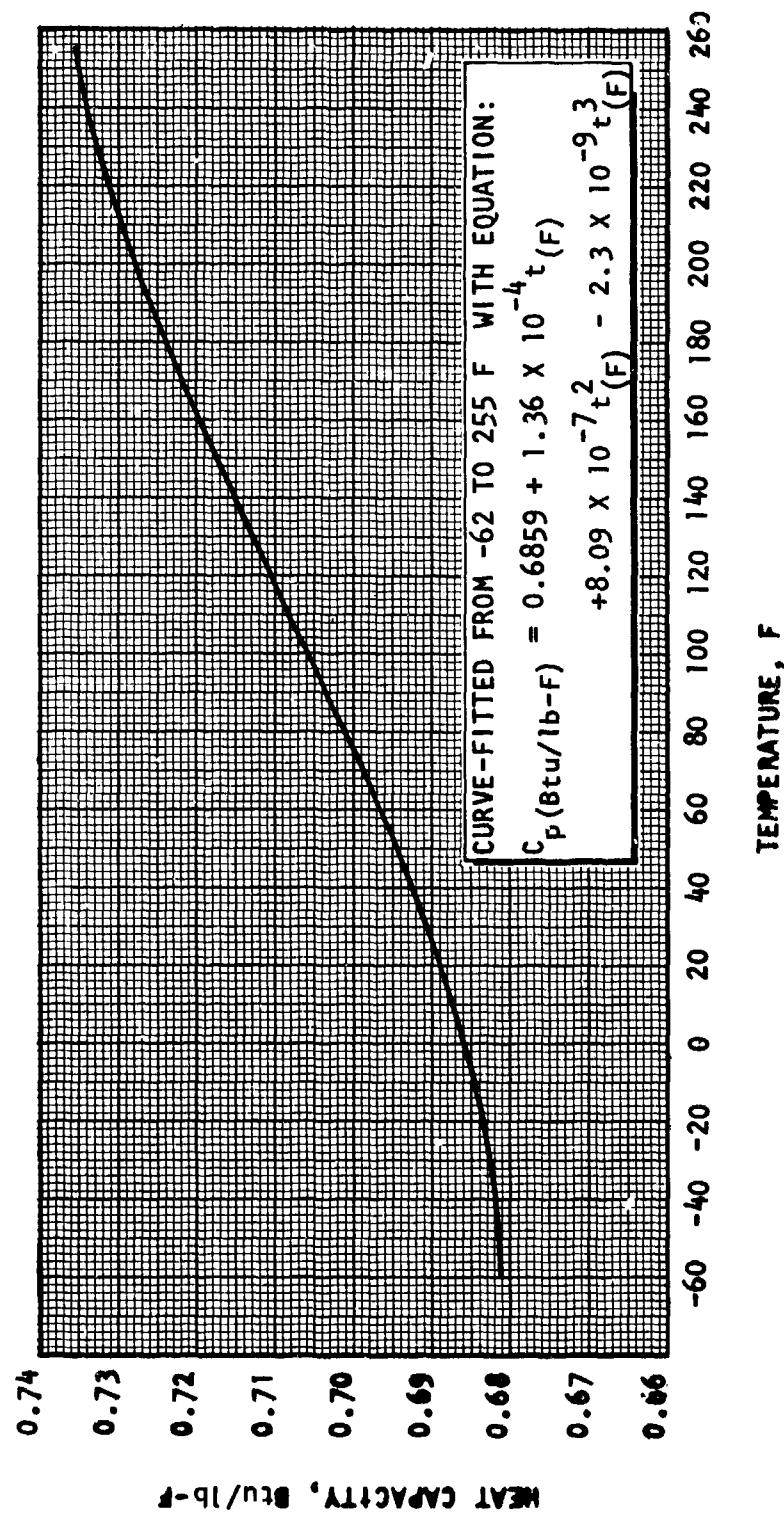


Figure A-6a. Heat Capacity of Liquid Monomethylhydrazine (Ref. A-2 and A-9)

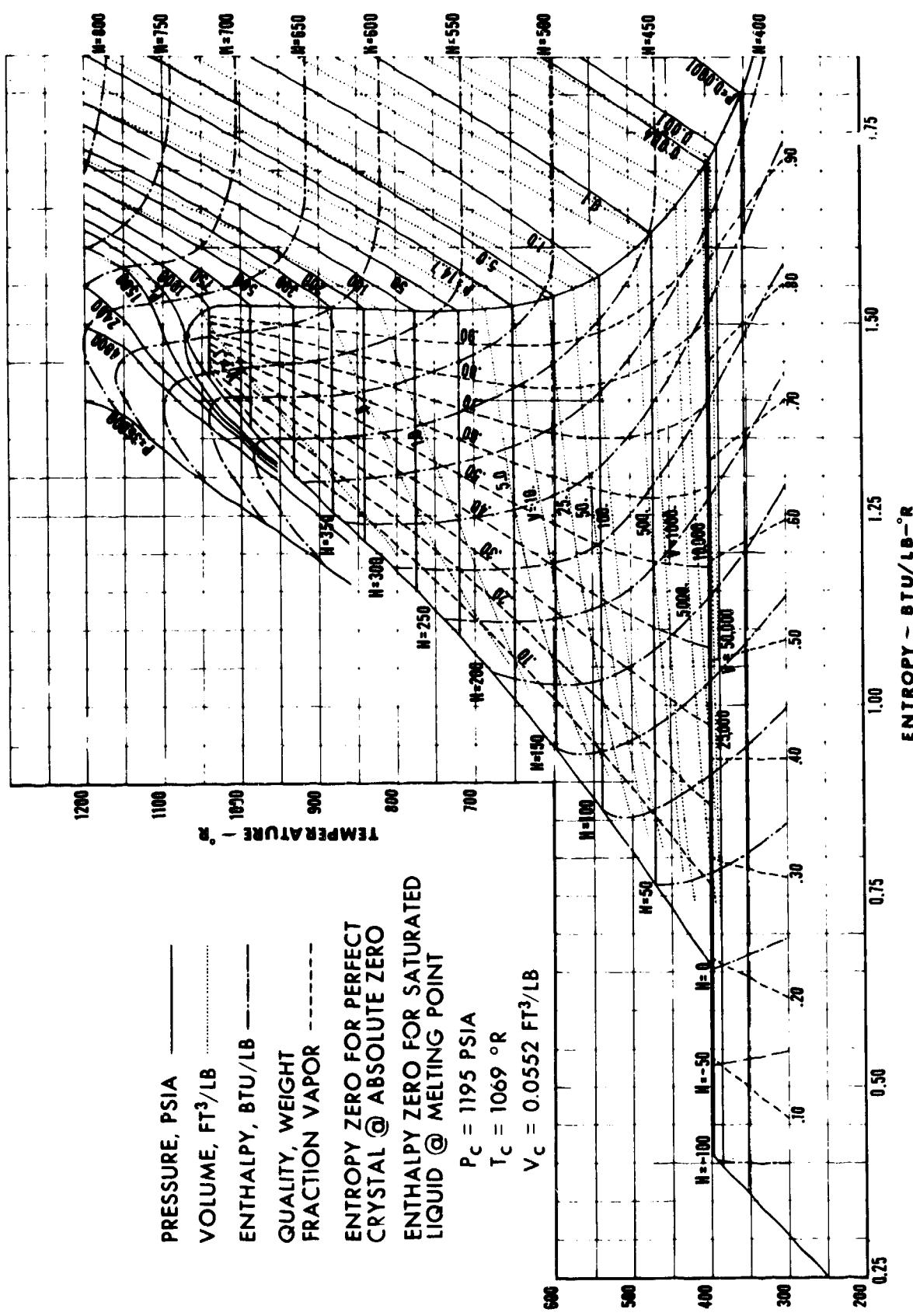


Figure A-7. Temperature vs Entropy Diagram for Monomethylhydrazine (Ref. A-10)

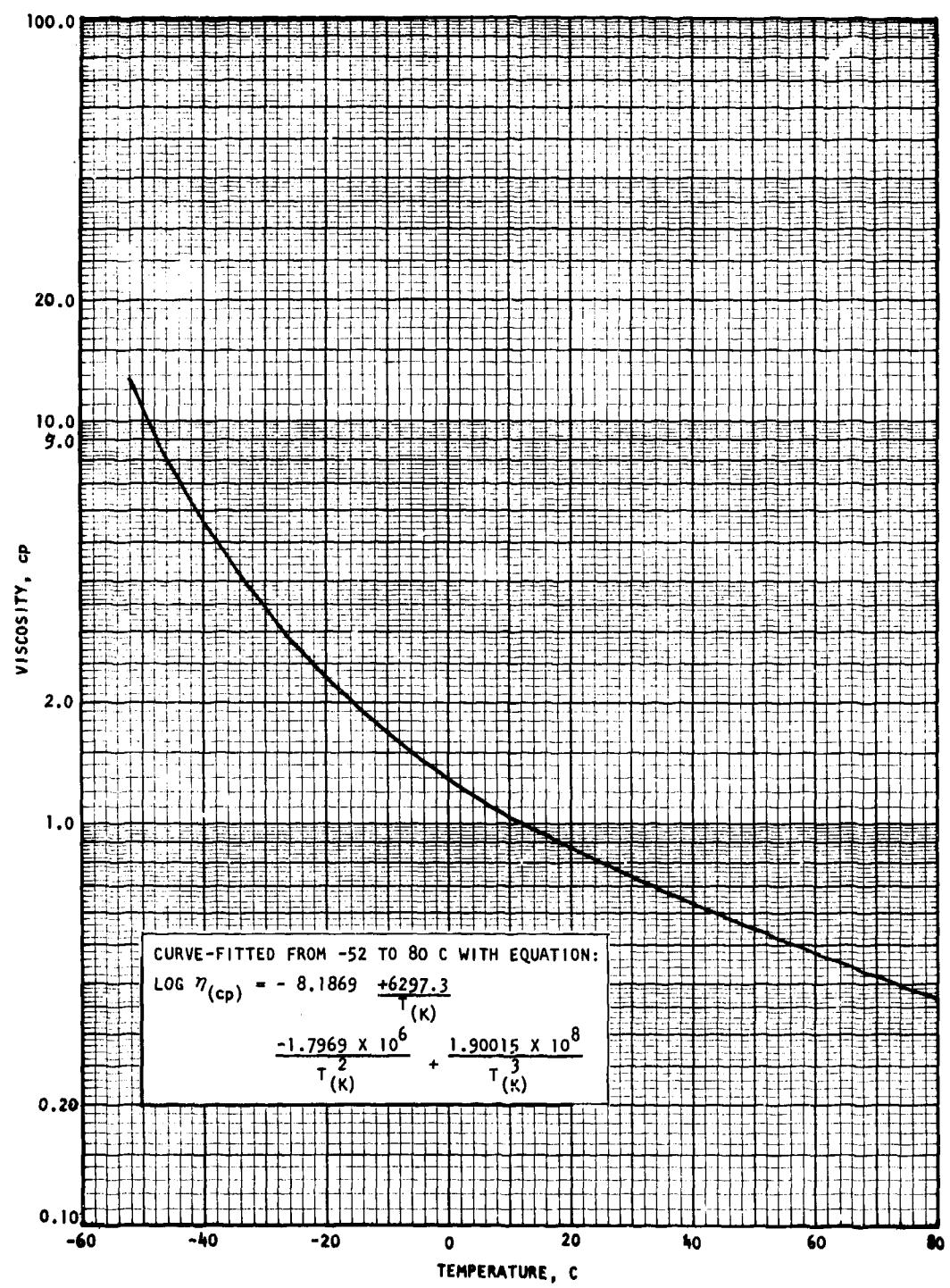


Figure A-8. Viscosity of Liquid Monomethylhydrazine (Ref. A-3 and A-11)

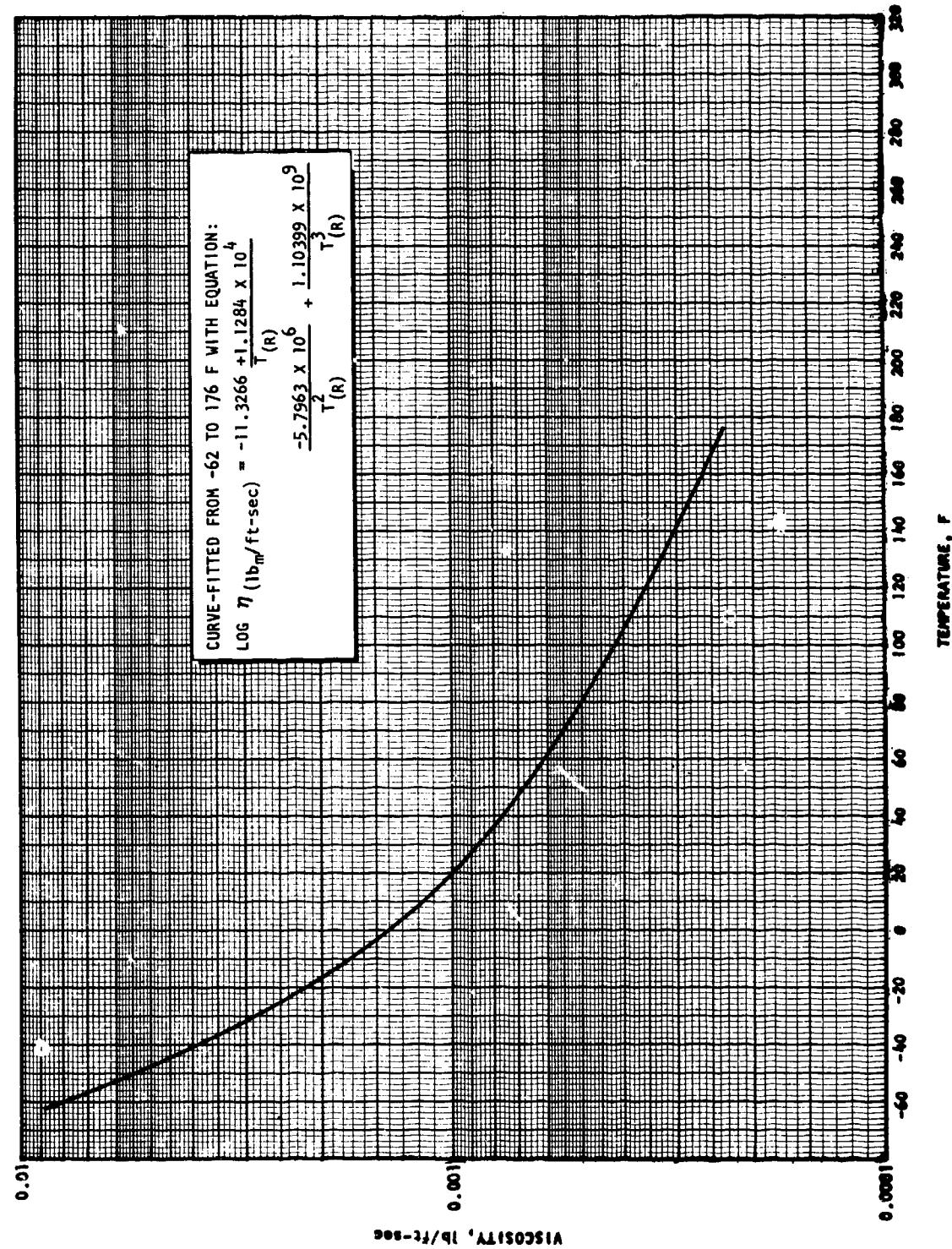


Figure A-8a. Viscosity of Liquid Monomethylhydrazine (Ref. A-3 and A-11)

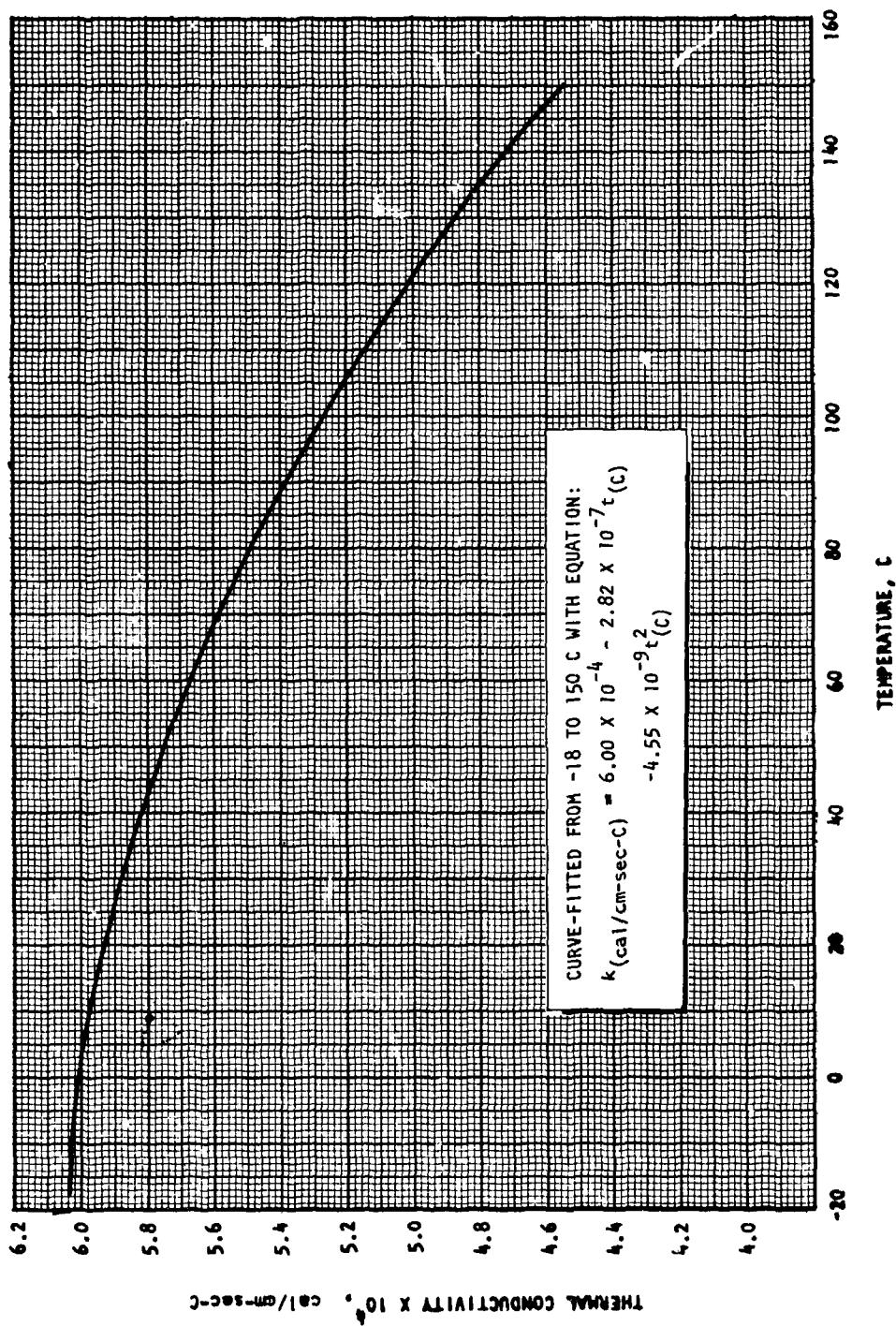


Figure A-9. Thermal Conductivity of Liquid Monomethylhydrazine (Ref. A-9)

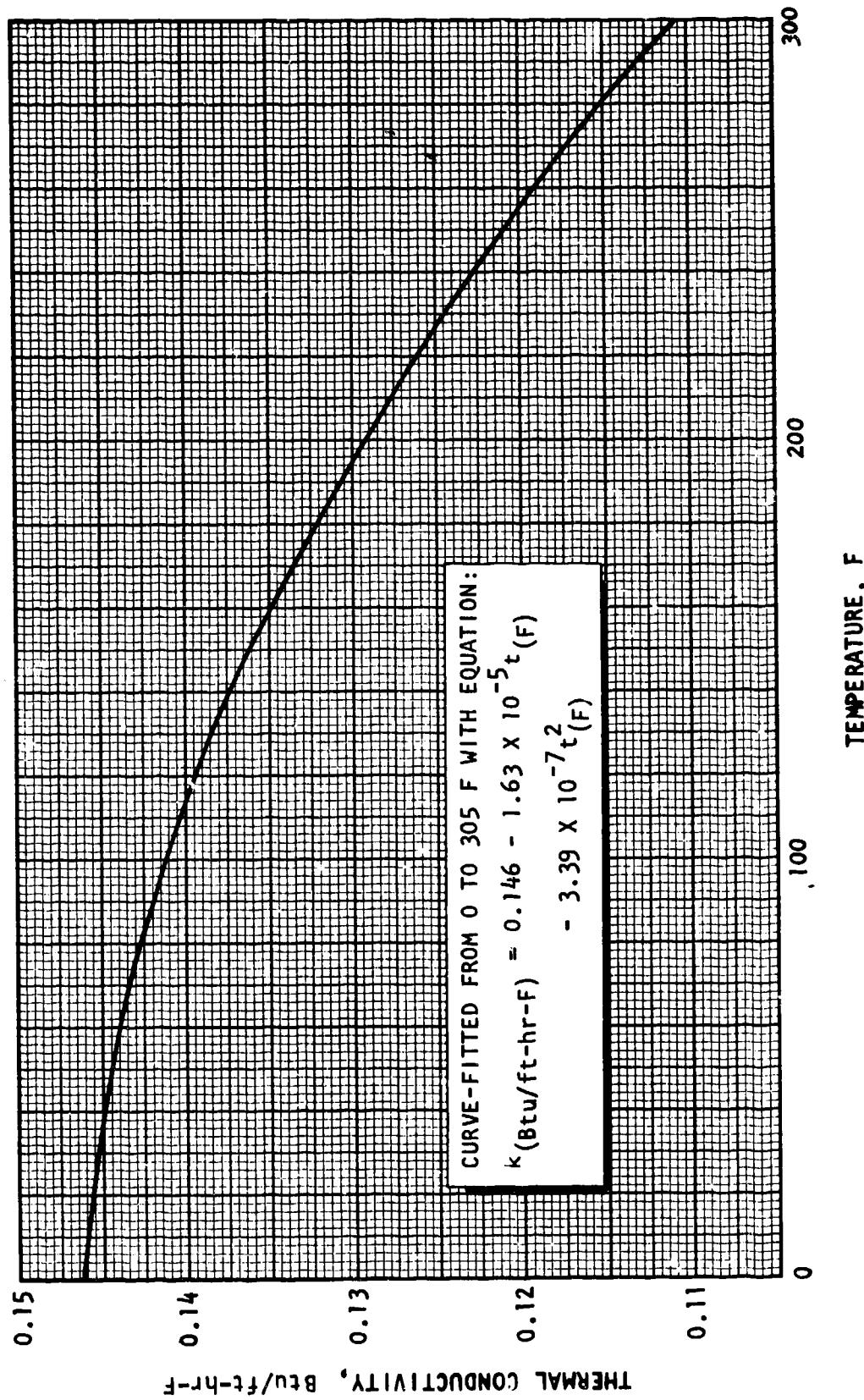


Figure A-9a. Thermal Conductivity of Liquid Monomethylhydrazine (Ref. A-9)

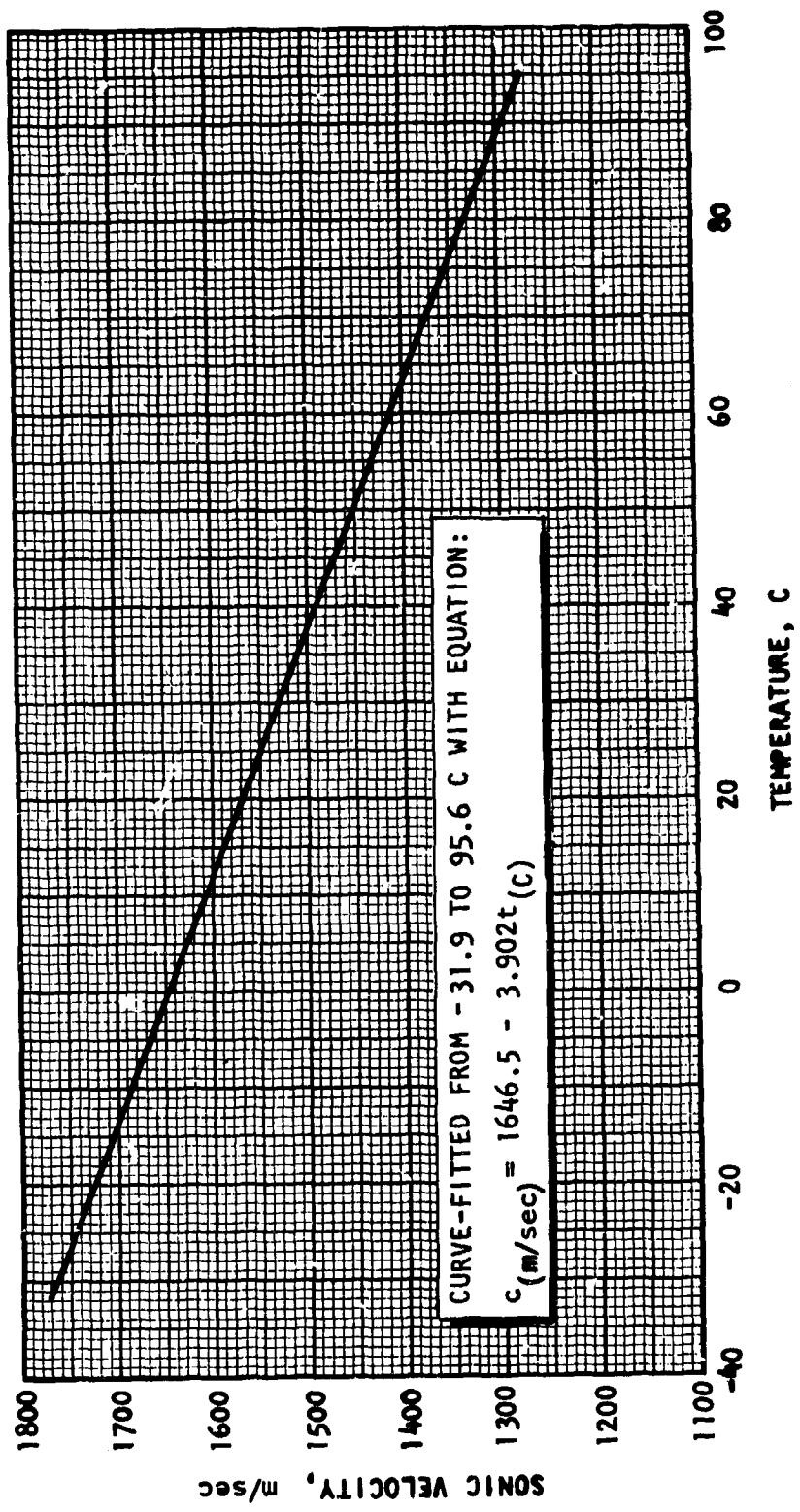


Figure A-10. Velocity of Sound in Saturated Liquid Monomethylhydrazine (Ref. A-5)

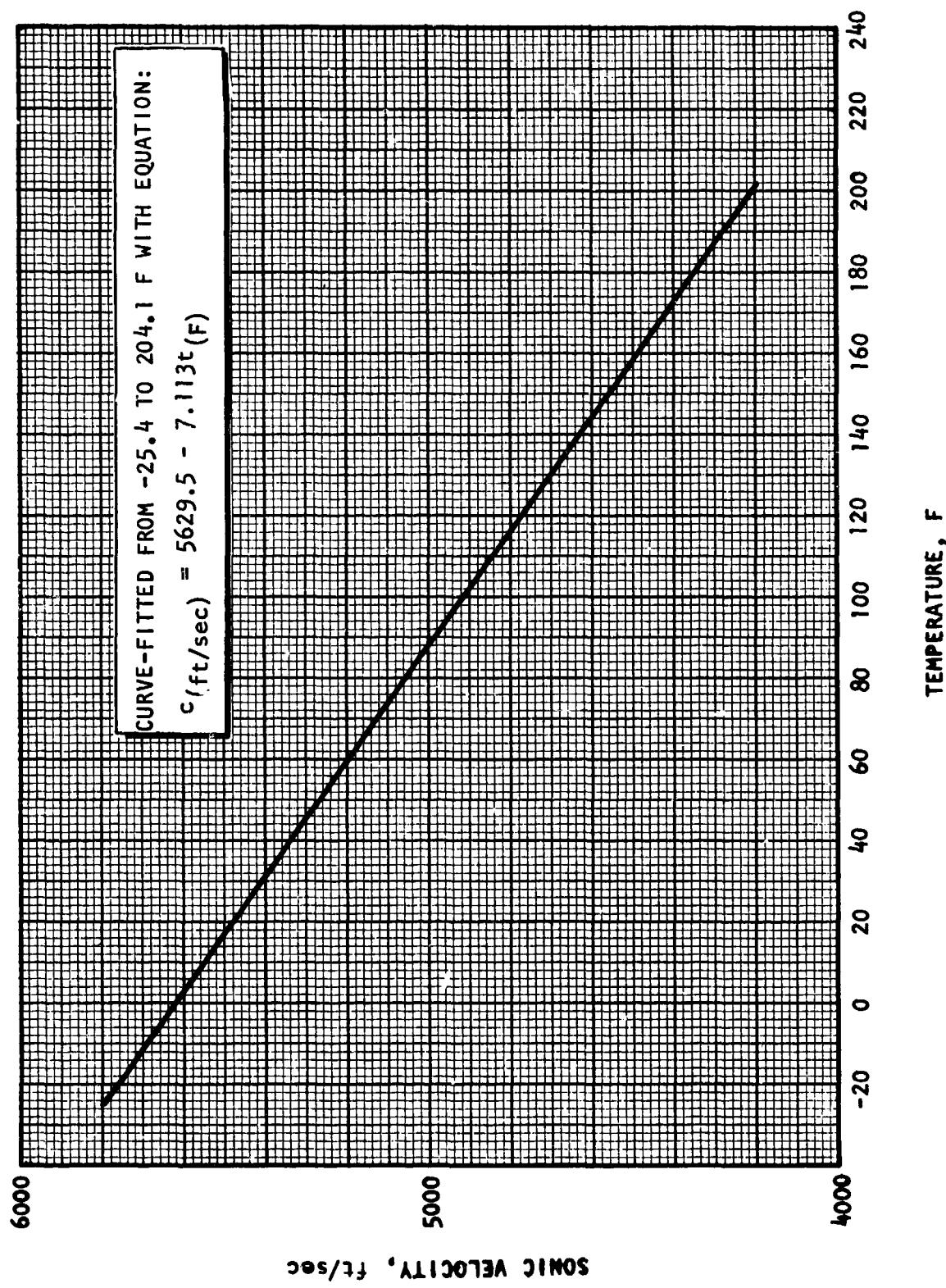


Figure A-10a. Velocity of Sound in Saturated Liquid Monomethylhydrazine (Ref. A-5)

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APPENDIX B

PHYSICAL PROPERTIES OF CYANOGEN

(U) The physical and thermodynamic properties of cyanogen are presented in Tables B-1 through B-3. Figures B-1 through B-5a are graphical illustrations of the properties listed in Table B-1.

TABLE B-1

PHYSICAL PROPERTIES OF CYANOGEND

Property	Value		Figure Number	Reference Number
	Metric	English		
<u>General Identification</u>				
Identification	Cyanogen			
Molecular Formula	C_2N_2			B-1
Molecular Weight	52.036			B-2
Freezing (Melting) Point	-27.88 C	-18.18 F		B-2
Triple Point	-27.88 C, 553.6 mm	-18.18 F, 10.7 psia		B-2
Normal Boiling Point	-21.20 C	-6.16 F		B-2
<u>Critical Properties</u>				
Temperature	128.3 C	262.9 F		B-3
Pressure	59.75 atm	878.3 psia		B-3
<u>Density</u>				
Solid	0.9544 g/cc at NBP	59.58 lb/cu ft at NBP	B-1, -1a	B-4
Liquid	2.321 g/l at STP	0.145 lb/cu ft at STP	B-4	B-4
Vapor (Saturated)	$\left(\frac{1}{V} \left(\frac{\partial V}{\partial T}\right)_P\right) 1.95 \times 10^{-3}/C^*$ at NBP	$1.08 \times 10^{-3}/F^*$ at NBP	-	-
<u>Phase Properties</u>				
Density				
Adiabatic				
Isothermal				

*Calculated Data

TABLE B-1
(Continued)

PHYSICAL PROPERTIES OF CYANOGEN

Property	Metric	Value	Figure Number	Reference Number
<u>Phase Properties</u> (Continued)				
Vapor Pressure				
Solid	342.2 mm at -35 C	6.62 psia at -31 F	B-2	B-2, -5
Liquid	5.59 atm at 25 C	82.2 psia at 77 F	B-3	B-2, -4, -5, -6
Surface Tension	21.98 dynes/cm at NBP	1.506×10^{-5} lb/ft at NBP	B-4	B-4
Thermodynamic Properties				
Heats of				
Formation (gas)	73.87 \pm 0.43 Kcal/mole at 25 C	2555.9 Btu/lb at 77 F	B-7	B-7
Fusion	1938 cal/g-mole at MP	67.04 Btu/lb at MP	B-2	B-2
Vaporization	5576 cal/g-mole at NBP	192.88 Btu/lb at NBP	B-2	B-2
Sublimation	7750 cal/g-mole at MP	268.15 Btu/lb at MP	B-5	B-5
Heat Capacity				
Solid	20.702 cal/mole-K at 240K	0.3979 Btu/1b-R at 432 R	B-5, -5a	B-2
Liquid	25.175 cal/mole-K*	0.4839 Btu/1b-R*	B-2	B-2
Gas (ideal)	—	—	Table B2	B-8
Cp	—	—	Table B2	B-8
Cv	—	—	Table B2	B-8
Entropy	—	—	Table B2	B-8
Enthalpy	—	—	Table B2	B-8

*Because the heat capacity data for the liquid are nearly independent of temperature over the range of the measurements (-27 to -19 C), an average value is reported.

TABLE B-1

(Concluded)

PHYSICAL PROPERTIES OF CYANOGEN

Property	Value		Figure Number	Reference Number
	Metric	English		
<u>Transport Properties</u>				
Viscosity				
Liquid	—	—	Table B-3	B-9
Gas	—	—	Table B-3	B-9
Thermal Conductivity				
Liquid	—	—	Table B-3	B-9
Gas	—	—	Table B-3	B-9
Sonic Velocity				
<u>Electromagnetic Properties</u>				
Index of Refraction				
Solid				
Liquid				
Gas				
Dipole Moment	$n_{5462.25} \text{ \AA} = 1.000752$ at 25 C (77 F), 1 atm	~0		
Dielectric Constant				
Liquid	2.52 at 23 C (73.4 F)		B-14	
Gas	1.0002529 at 25 C (77 F), 1 atm (14.7 psia)		B-13	
Electrical Conductivity	$< 7 \times 10^{-9} \text{ ohm}^{-1} \text{ cm}^{-1}$		B-15	
Magnetic Susceptibility (χ_M)	$-22.5 \times 10^{-6} \text{ cgsm}$		B-16	
<u>General Description</u>				
Appearance: Colorless liquid or gas				
Odor: Pungent, penetrating odor				
Toxicity: Threshold Limit Value (TLV) = 5 mg/m ³				

TABLE B-2

THERMODYNAMIC PROPERTIES OF CYANOGEN
(IDEAL GAS) (REF. B-8)

Temperature		Heat Capacity		Entropy		Enthalpy ($H_T - H_{298(g)}$)	
K	R	cal/mole-K	Btu/lb-R	cal/mole-K	Btu/lb-R	Kcal/mole	Btu/lb
0	0	0	0	0	0	-3.018	-104.44
100	180	8.700	0.167	45.654	0.877	-2.275	-78.69
200	360	11.690	0.225	52.663	1.012	-1.247	-43.13
298	536.4	13.563	0.260	57.711	1.109	0	0
300	540	13.590	0.261	57.795	1.110	0.025	0.86
400	720	14.771	0.284	61.878	1.189	1.447	50.05
500	900	15.615	0.300	65.269	1.254	2.968	102.67
600	1080	16.305	0.313	68.178	1.310	4.565	157.91
700	1260	16.899	0.325	70.737	1.359	6.226	215.36
800	1440	17.415	0.335	73.028	1.403	7.942	274.72
900	1620	17.858	0.343	75.106	1.443	9.707	335.77
1000	1800	18.237	0.350	77.007	1.479	11.512	398.21
1500	2700	19.434	0.373	84.660	1.626	20.969	725.34
2000	3600	19.993	0.384	90.337	1.735	30.842	1066.23
2500	4500	20.285	0.390	94.833	1.822	40.919	1415.43
3000	5400	20.454	0.393	98.548	1.893	51.107	1767.84
3500	6300	20.559	0.395	101.709	1.954	61.362	2122.57
4000	7200	20.629	0.396	104.459	2.007	71.660	2478.79
4500	8100	20.678	0.397	106.892	2.053	81.988	2836.05
5000	9000	20.713	0.398	109.072	2.095	92.336	3193.99
5500	9900	20.739	0.398	111.048	2.133	102.699	3552.46
6000	10800	20.759	0.399	112.853	2.168	113.074	3911.34

TABLE B-3
IDEAL VISCOSITY AND THERMAL CONDUCTIVITY
OF CYANOGEN GAS (REF. B-9)

Temperature		Viscosity		Thermal Conductivity	
K	R	Micropoise	10^{10} lb/ft-sec	10^6 cal/cm-sec-K	10^3 Btu/ft-hr-F
100	180	35.8	2.41	8.5	2.06
200	360	67.8	4.56	21.3	5.15
300	540	102.3	6.87	37.0	8.95
400	720	136.5	9.17	53.5	12.94
500	900	159.2	11.37	69.9	16.91
600	1080	199.9	13.43	86.1	20.82
700	1260	228.6	15.36	101.9	24.64
800	1440	255.6	17.18	117.3	28.37
900	1620	281.1	18.89	132.2	31.97
1000	1800	305.4	20.52	146.5	35.43
1200	2160	350.9	23.58	173.6	41.99
1400	2520	392.8	26.40	198.7	48.06
1600	2880	432.1	29.04	222.0	53.69
1800	3240	469.0	31.52	243.8	58.96
2000	3600	504.2	33.88	264.4	63.95
2200	3960	538.0	36.15	284.0	68.69
2400	4320	570.6	38.34	302.8	73.23
2600	4680	602.1	40.46	320.8	77.59
2800	5040	632.6	42.51	338.1	81.77
3000	5400	662.1	44.49	354.9	85.84
3200	5760	690.7	46.42	371.0	89.73
3400	6120	718.5	48.28	386.7	93.53
3600	6480	745.6	50.10	401.9	97.20
3800	6840	772.0	51.88	416.7	100.8
4000	7200	797.8	53.61	431.2	104.3
4200	7560	823.2	55.32	445.3	107.7
4400	7920	848.1	56.99	459.2	111.1
4600	8280	872.6	58.64	472.9	114.4
4800	8640	896.9	60.27	486.4	117.6
5000	9000	921.1	61.90	499.7	120.9

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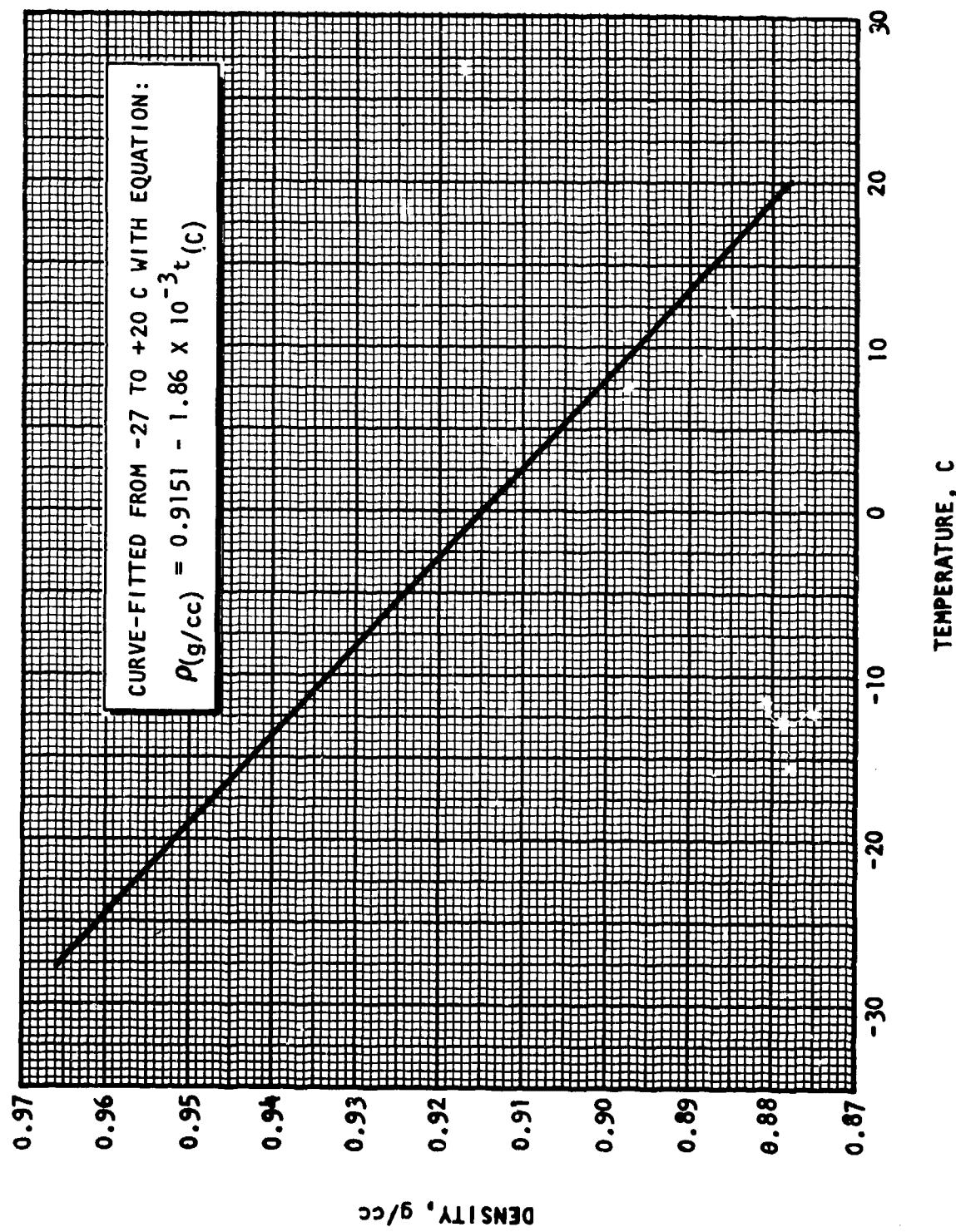


Figure B-1. Density of Saturated Liquid Cyanogen (Ref. B-4)

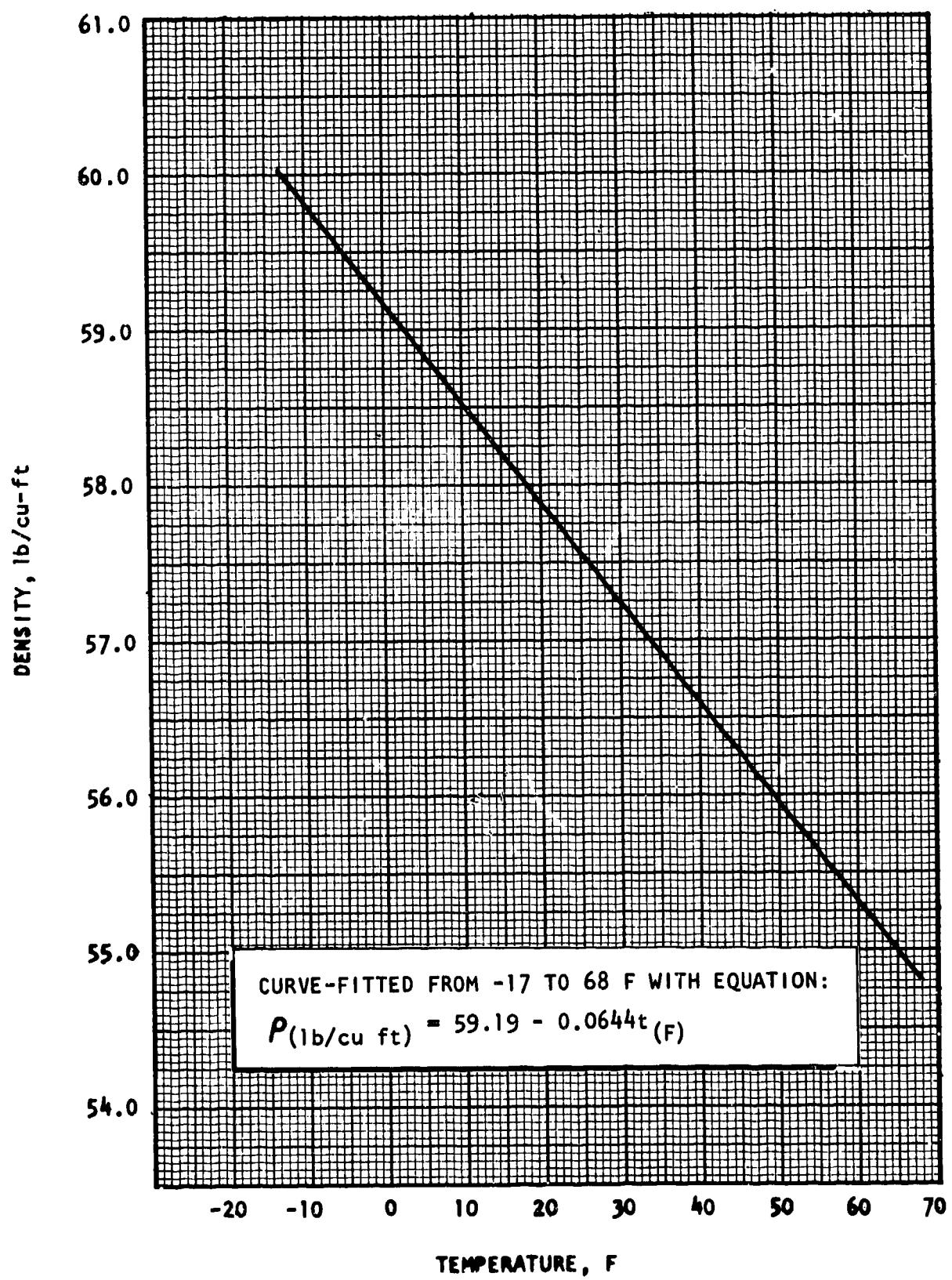


Figure B-1a. Density of Saturated Liquid Cyanogen (Ref. B-4)

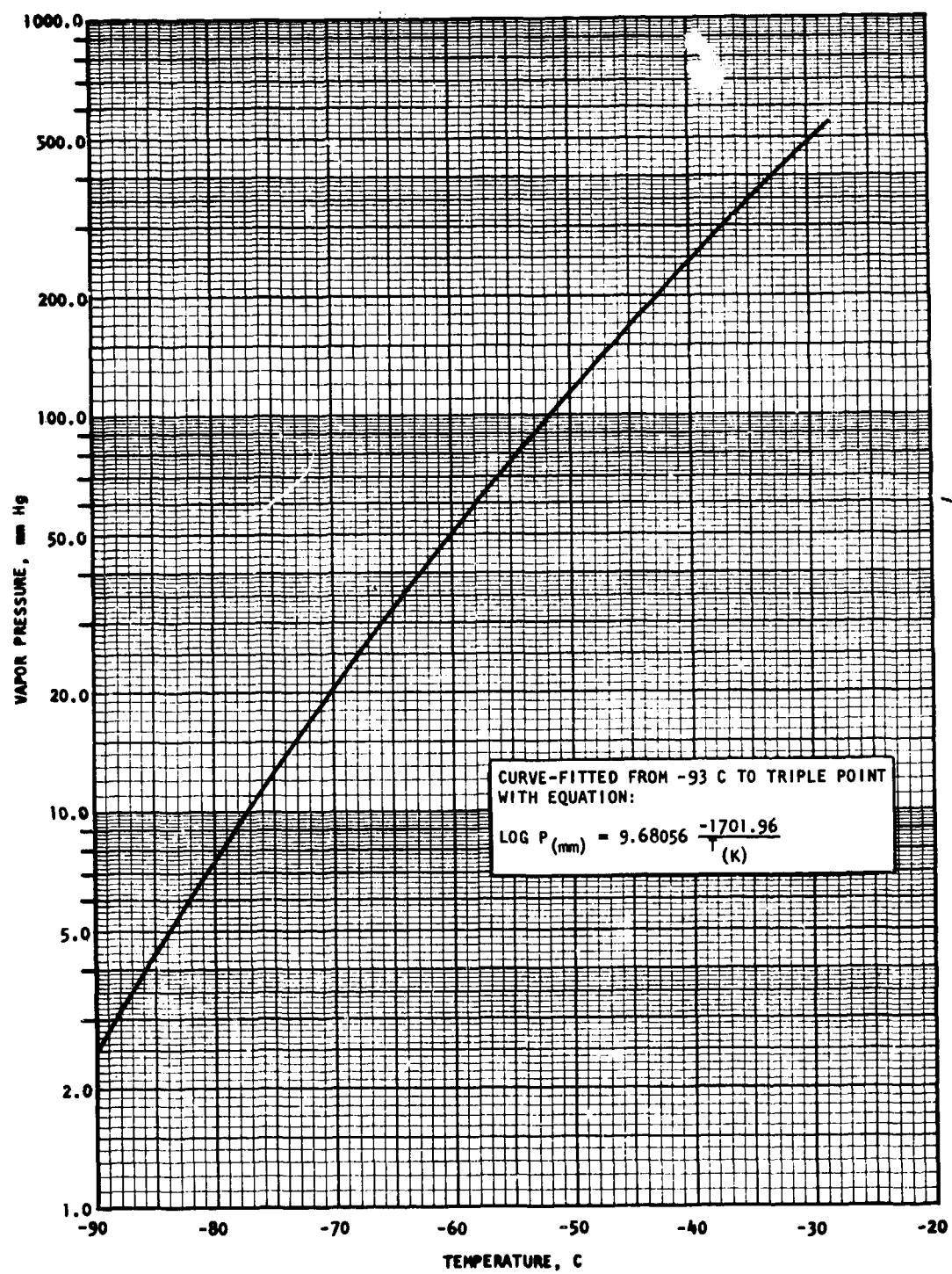


Figure B-2. Vapor Pressure of Solid Cyanogen (Ref. B-2 and B-5)

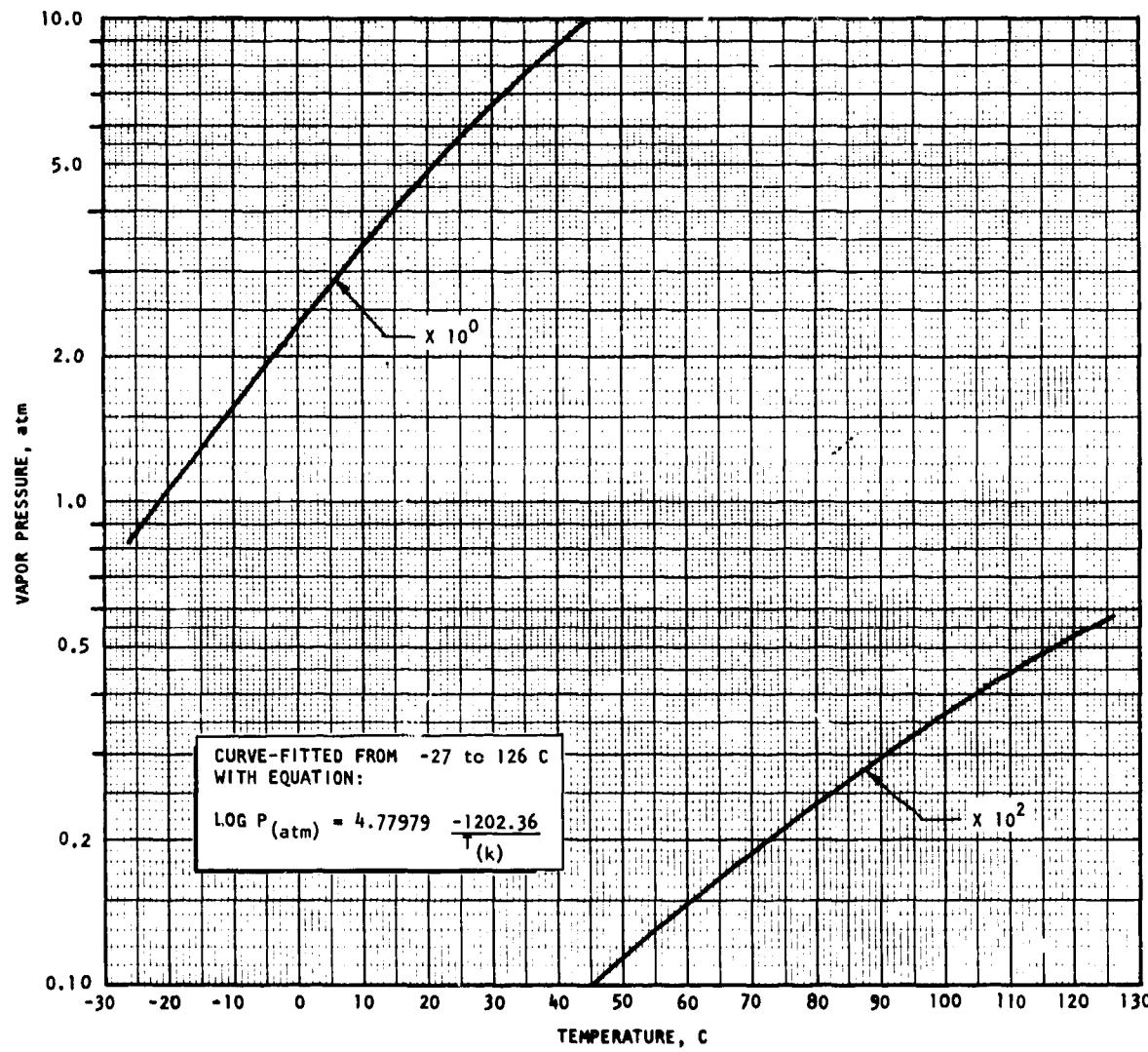


Figure B-3. Vapor Pressure of Liquid Cyanogen
(Ref. B-2 and B-4 through B-6)

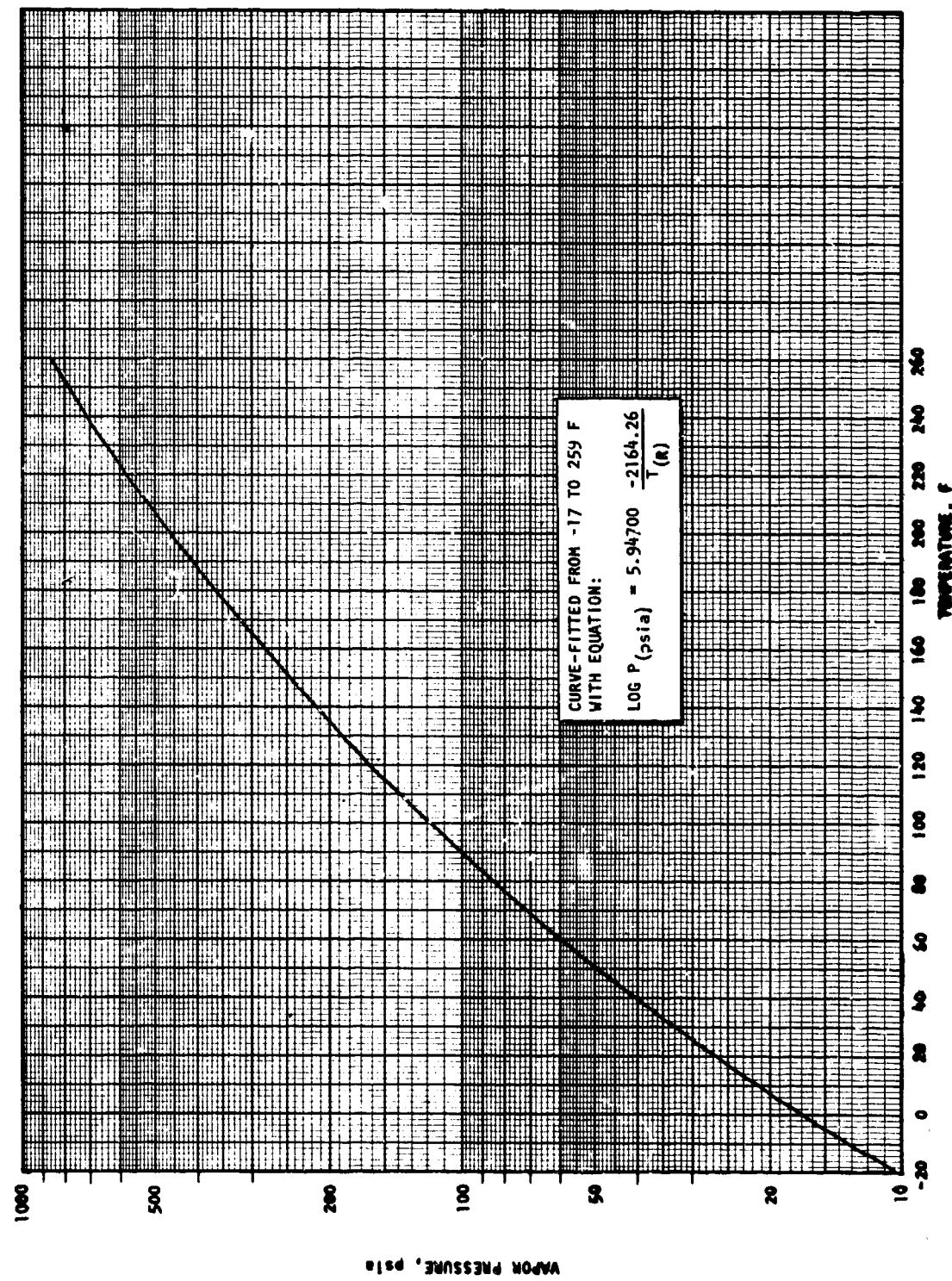


Figure B-3a. Vapor Pressure of Liquid Cyanogen (Ref. B-2 and B-4 through B-6)

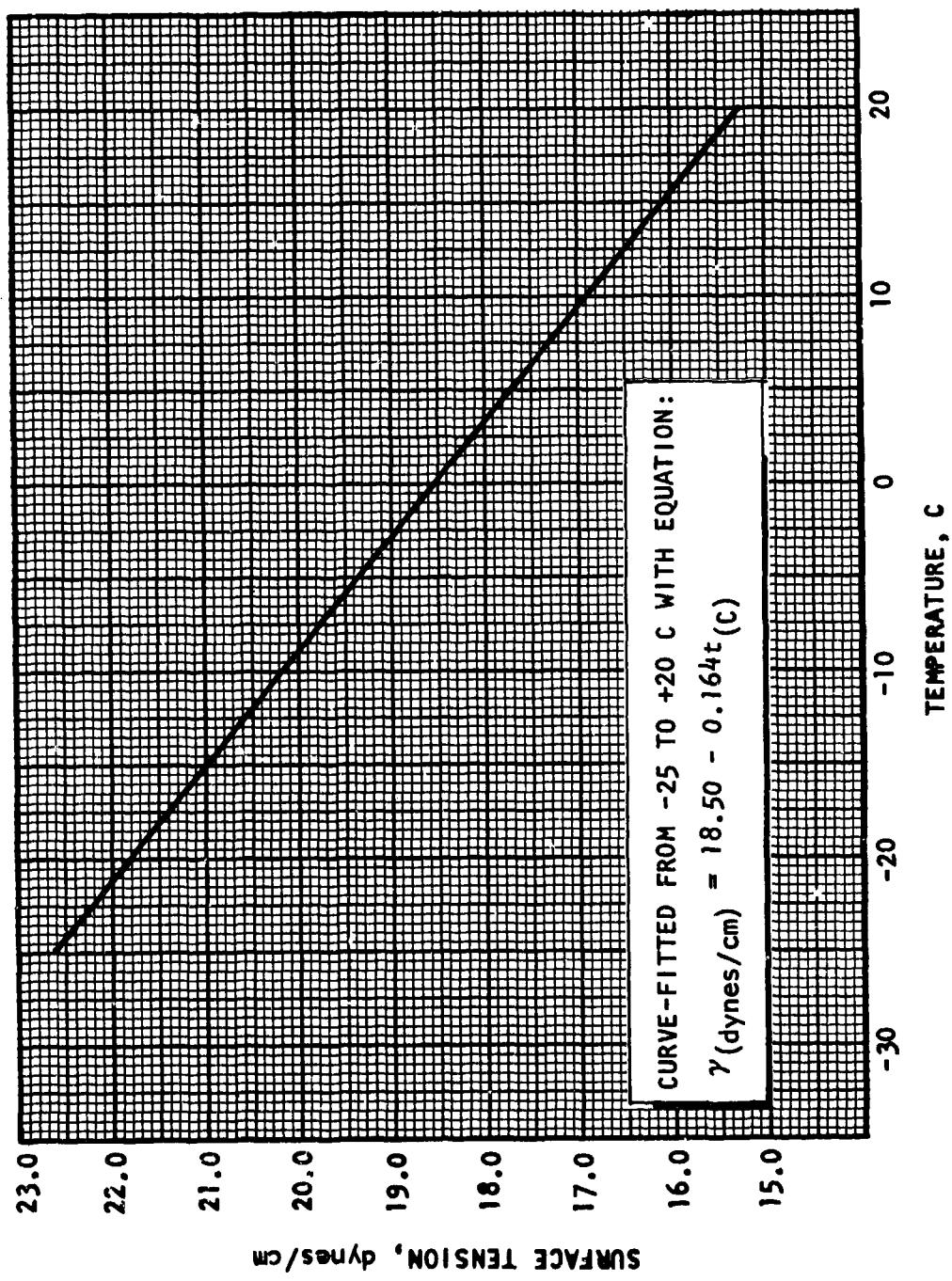


Figure B-4. Surface Tension of Saturated Liquid Cyanogen (Ref. B-4)

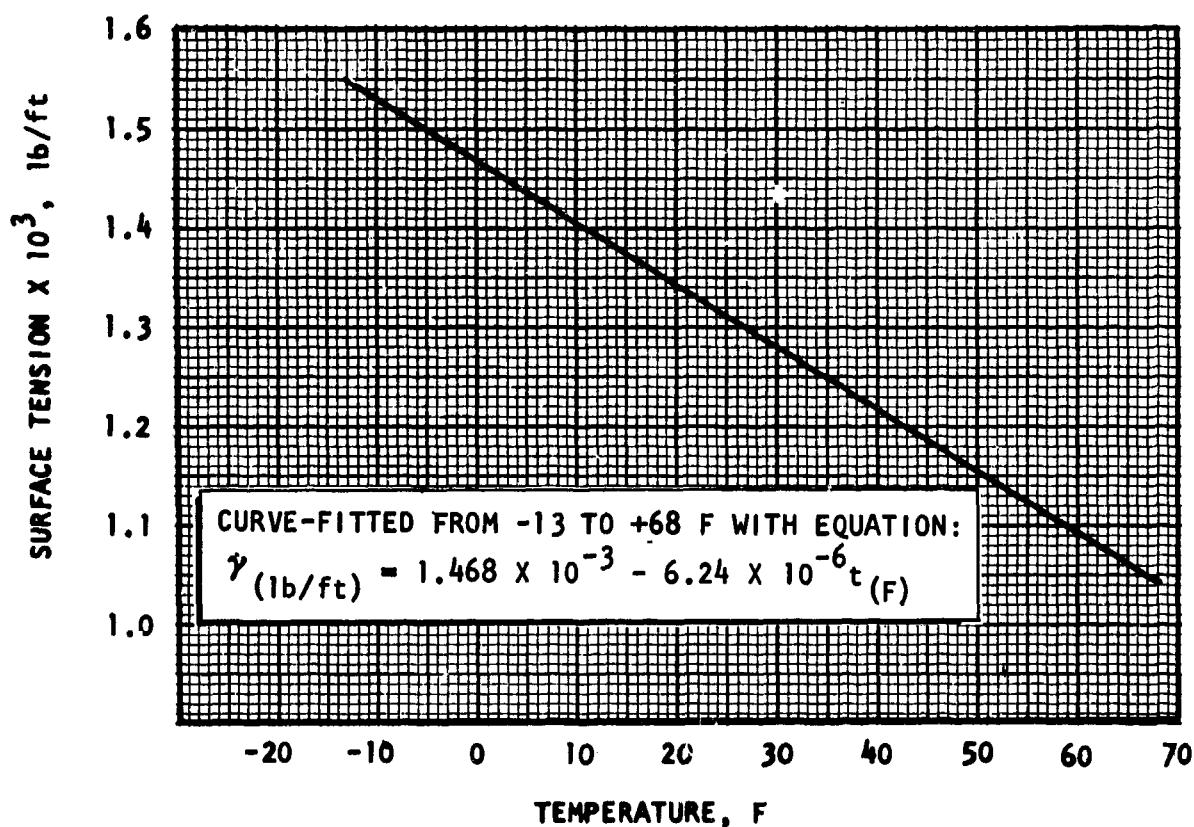


Figure B-4a. Surface Tension of Saturated Liquid Cyanogen (Ref. B-4)

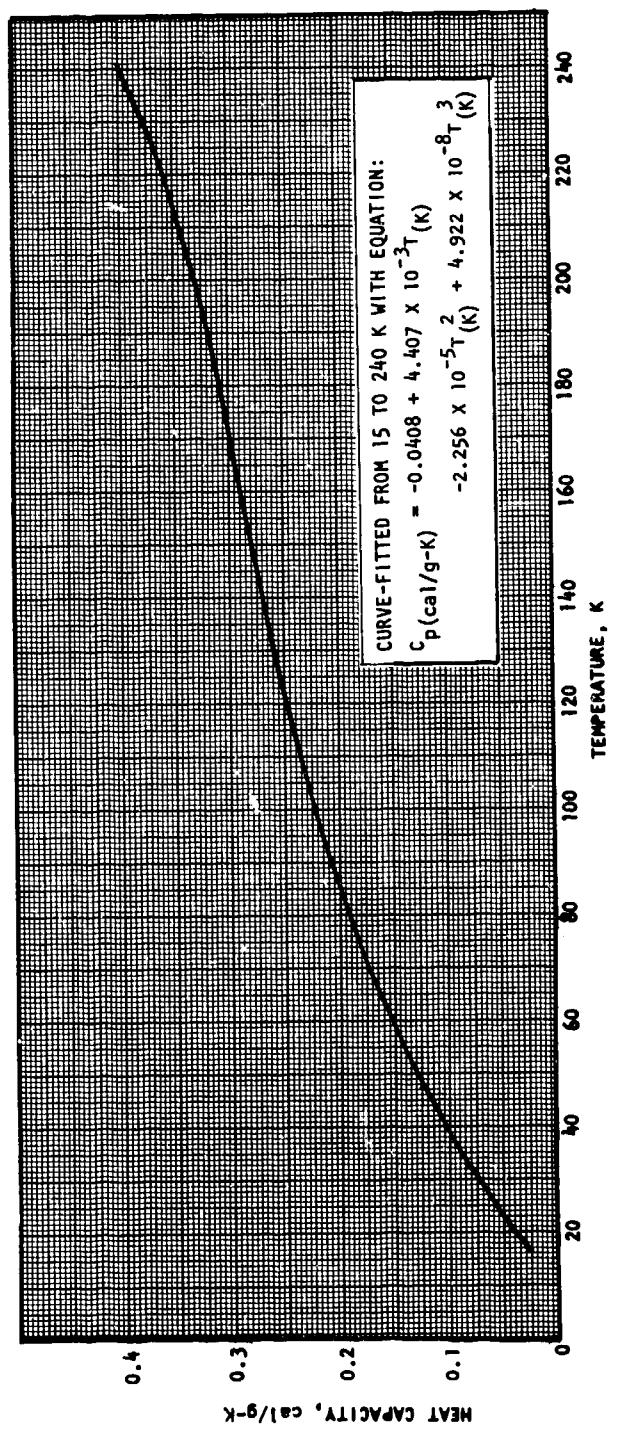


Figure B-5. Heat Capacity of Solid Cyanogen (Ref. B-2)

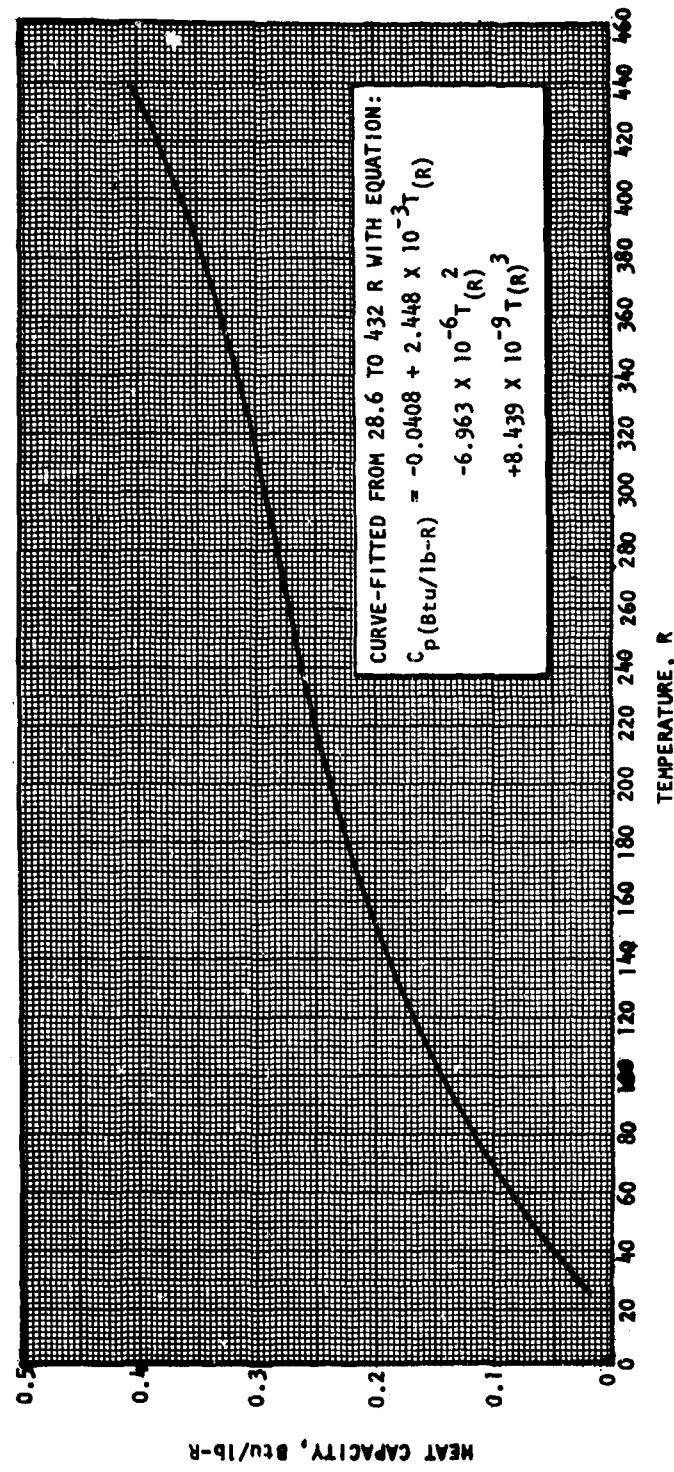


Figure B-5a. Heat Capacity of Solid Cyanogen (Ref. B-2)

APPENDIX C

PHYSICAL PROPERTIES OF THE MIXED OXIDES OF NITROGEN

(U) The physical and thermodynamic properties of the mixed oxides of nitrogen (solutions of NO in N_2O_4) are presented in Table C-1. Figures C-1 through C-8a are graphical illustrations of the properties listed in Table C-1.

Table C-1
PHYSICAL PROPERTIES OF MIXED OXIDES OF NITROGEN (MON) AT 25 C (77 F)

Property	Metric	Value	English	Metric	Value	Metric	Value	English	Figure Number	Reference Number
<u>General Identification</u>										
Identification		MON 90-10		MON 75-25		MON 70-30				
Nominal Composition		90 w/o N_2O_4 -10 w/o NO		75 w/o N_2O_4 -25 w/o NO		70 w/o N_2O_4 -30 w/o NO				
Molecular Weight*	g/mole	87.344	87.344	81.182	81.182	79.327	79.327	79.327	C-1	C-1
Freezing Point	°C	-23	-9.4 F	8/g-mole	1.6b/lb-mole	1b/mol	1b/mol	1b/mol	C-1,4	C-2,6
Normal Boiling Point**	°C	9.7	49.4 F	-54 C	-65.2 F	-81 C	-113.8 F	-16.1 C	3.0 F	
Critical Properties				15.9 F						
Temperature										
Pressure										
Density										
Liquid	g/cc	1.408	87.89 lb/cu ft	1.379	86.07	1.371	85.56	85.56 1b/cu ft	C-2,-2a	C-4,7,8,9
Gas										
Thermal Expansion (cubic)										
Compressibility										
Adiabatic										
'Isothermal										
Vapor Pressure	atm	2.074	30.48 psia	5.096	74.39 psia	7.229 atm	106.2 psia	106.2 psia	C-4,-1a	C-2,4,7,10
Surface Tension†										
Thermodynamic Properties										
Heats of Formation (liquid)††		-0.278 Kcal/100g	-5.000 Btu/lb	+6.93 Kcal/100g	+124.7 Btu/lb	+9.34 Kcal/100g	+168.1 Btu/lb	+168.1 Btu/lb	C-12,13	
Fusion										
Vaporization										
Heat Capacity										
Liquid										
Gas										
Entropy										
Enthalpy										
Transport Properties										
Viscosity										
Liquid										
Gas										
Thermal Conductivity										
Liquid										
Gas										
Sonic Velocity										
Liquid										
Gas										
Electromagnetic Properties										
Index of Refraction										
Dipole Moment										
Dielectric Constant										
Electrical Conductivity										
Calculated Value										

*Based on NO present as N_2O_4

**Calculated from vapor pressure equation.

†Although additional values were determined in Ref.C-9, they were not included because of their questionable accuracy.

††Calculated Value.

GENERAL DESCRIPTION

Description: The mixed oxides of nitrogen (MON) designates a series of solutions of NO in N_2O_4 . The NO reacts with the N_2O_4 as it dissolves to form N_2O_3 , which is soluble in N_2O_4 .

Odor: Irritating and acid-like due to the NO.

Toxicity: Threshold Limit Value (TLV) = 5 ppm (9mg/cu ft) as NO.

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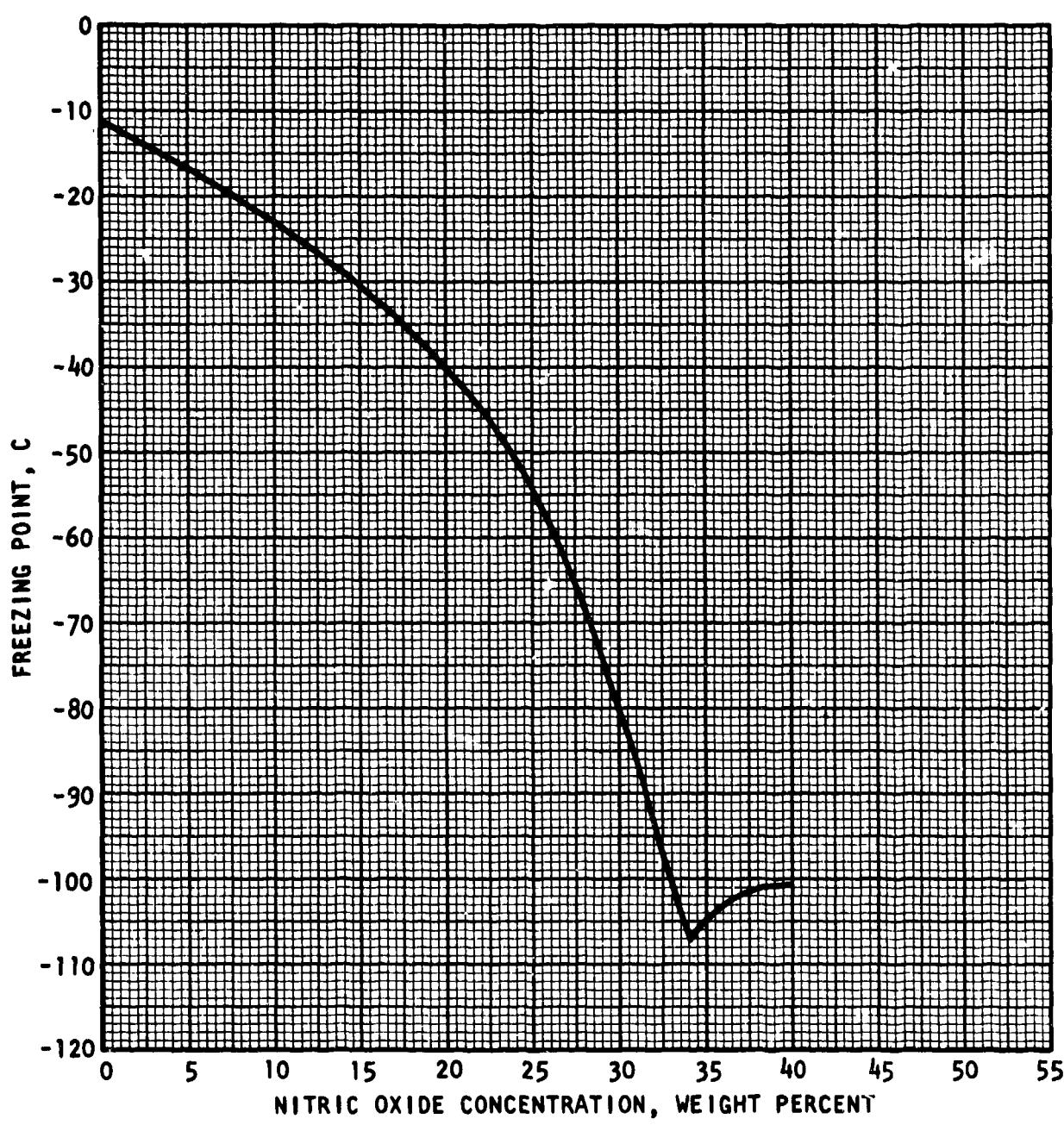


Figure C-1. Freezing Points of the Nitrogen Tetroxide-Nitric Oxide System (Ref. C-2 through C-6)

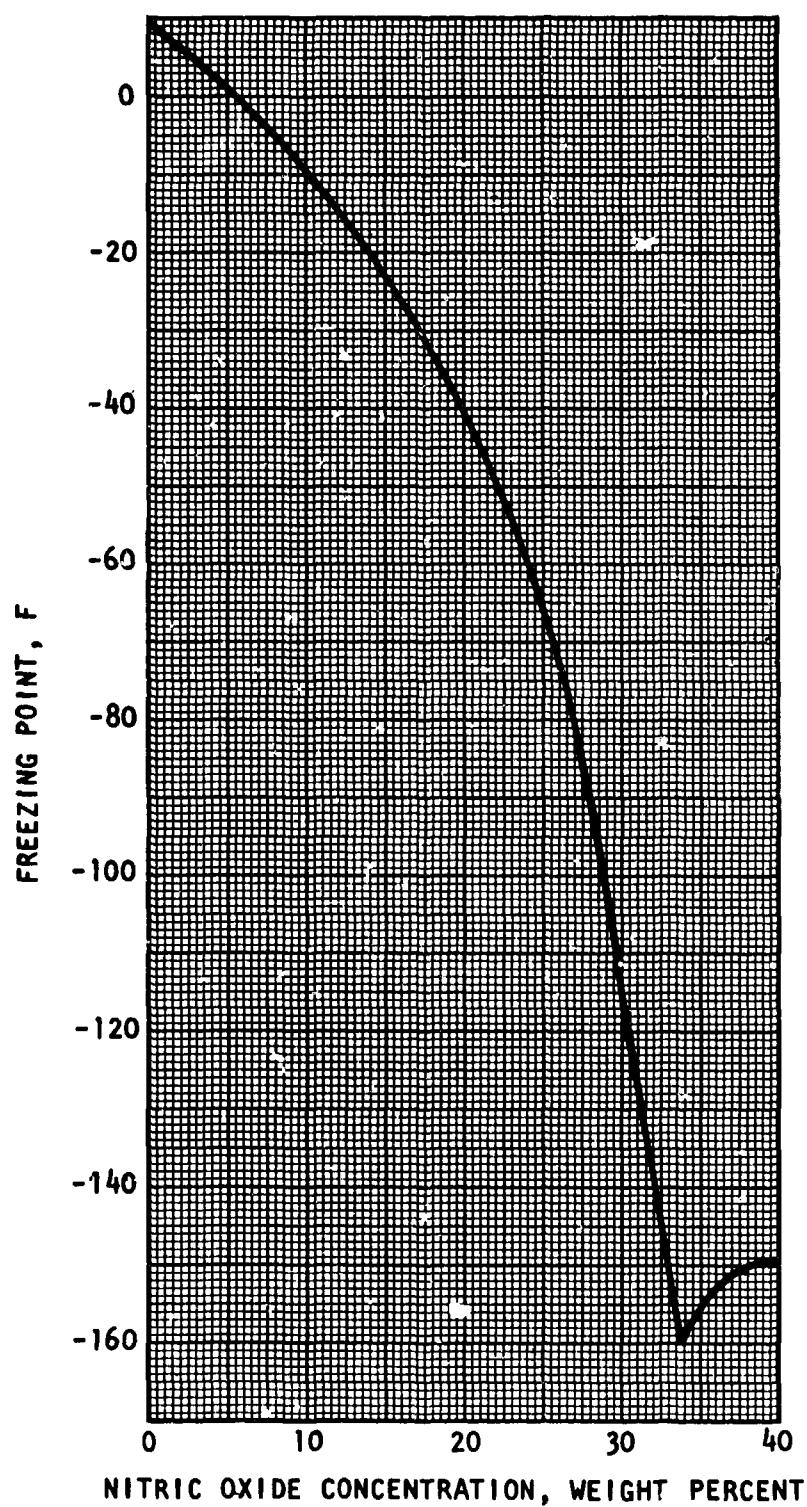


Figure C-1a. Freezing Points of the Nitrogen Tetroxide-Nitric Oxide System
(Ref. C-2 through C-6)

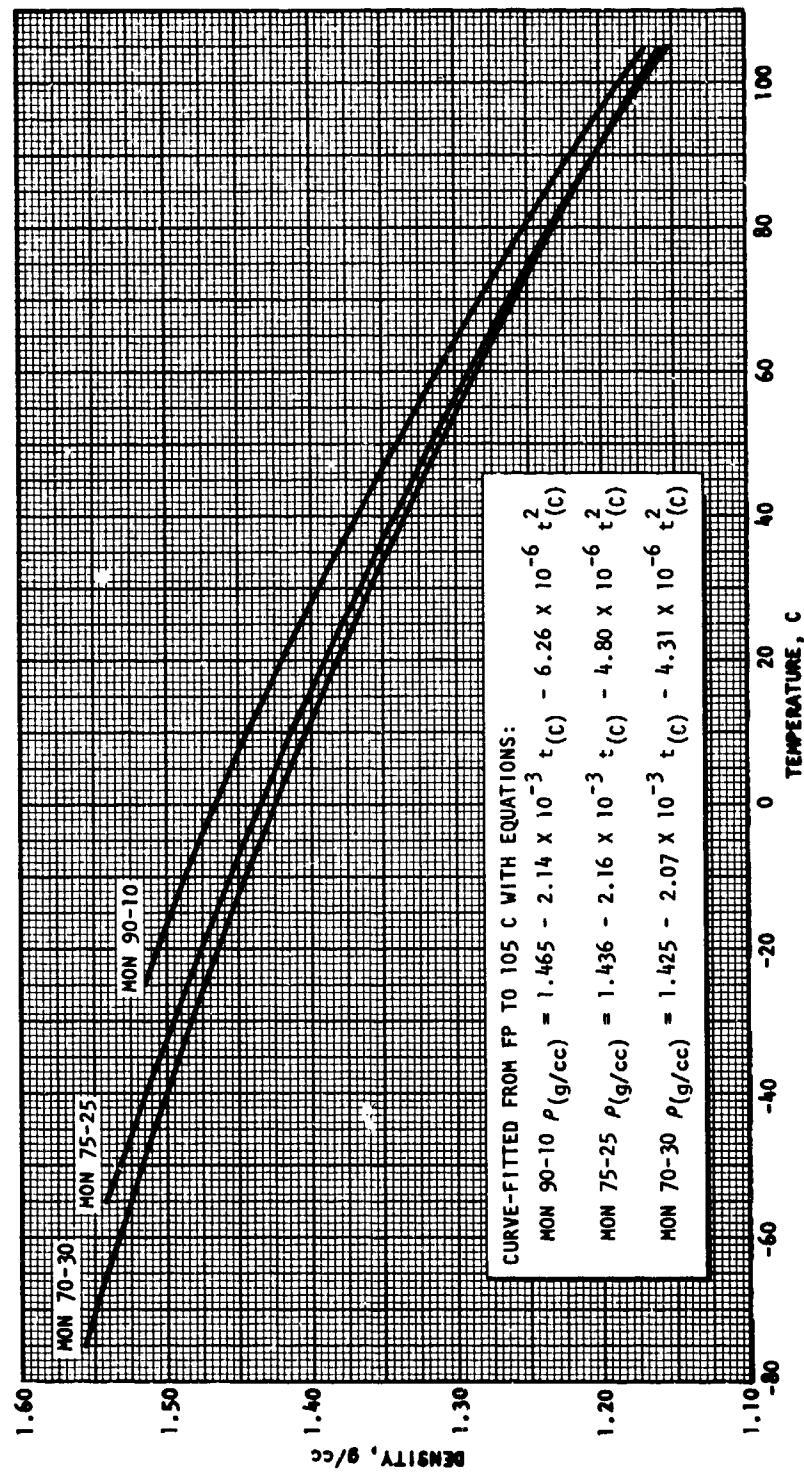


Figure C-2. Density of the Mixed Oxides of Nitrogen (Ref. C-4 and C-7 through C-9)

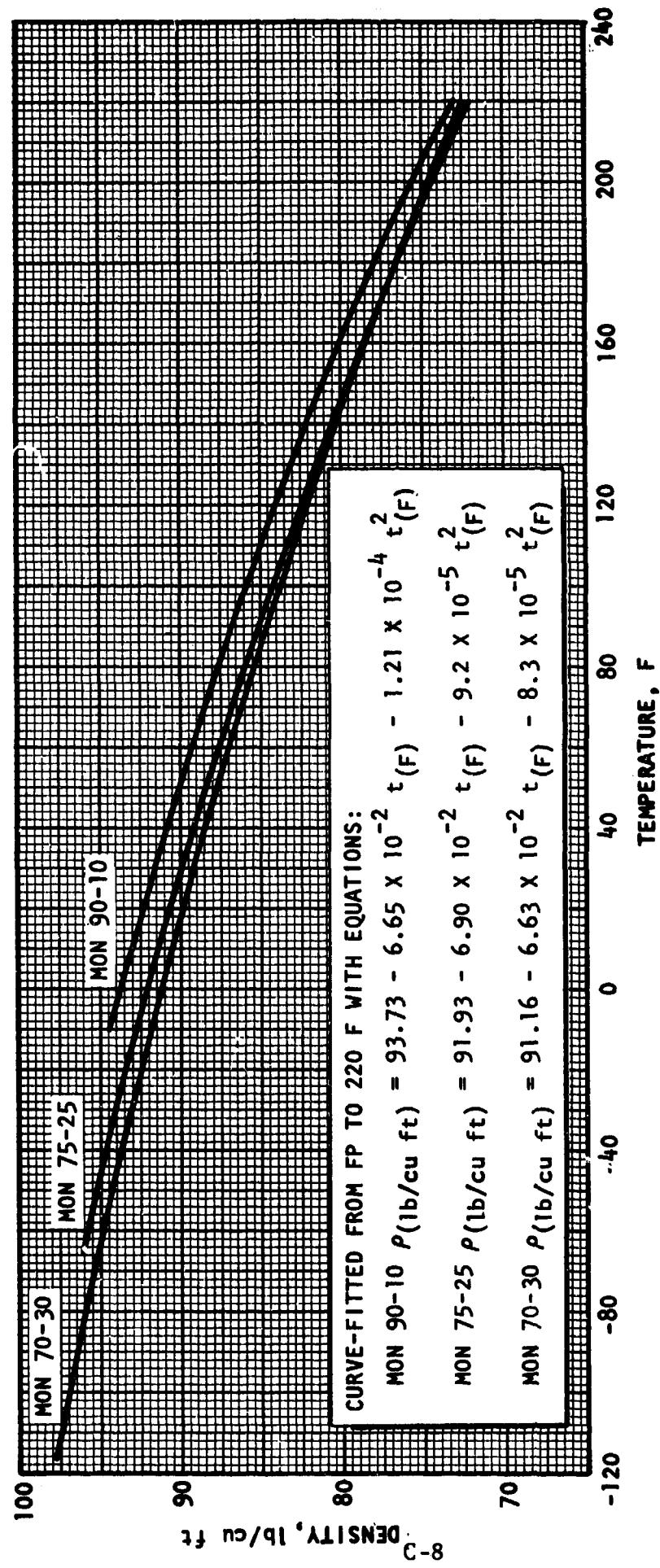


Figure C-2a. Density of the Mixed Oxides of Nitrogen (Ref. C-4, and C-7 through C-9)

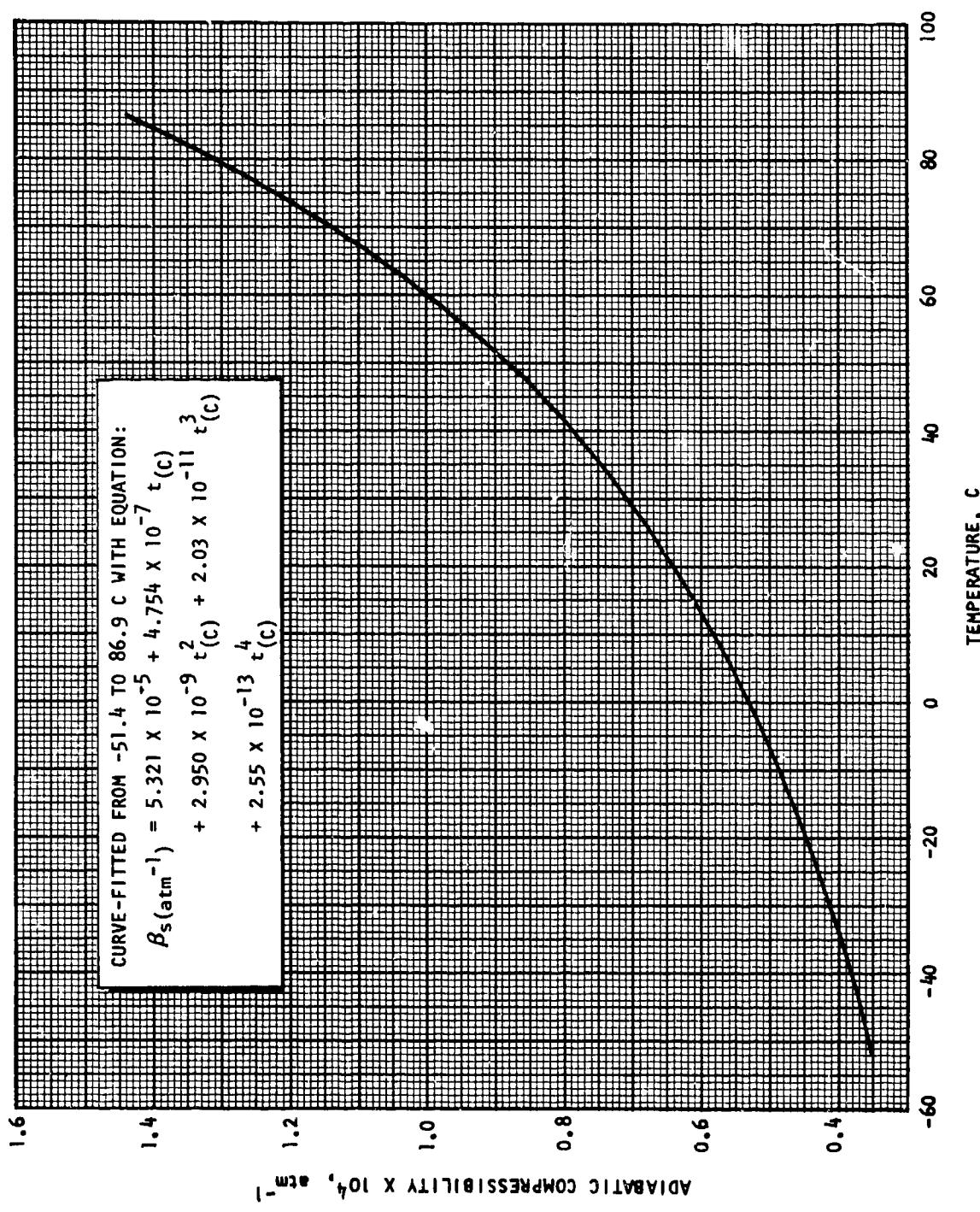


Figure C-3. Adiabatic Compressibility of MON-25 (Ref. C-11)

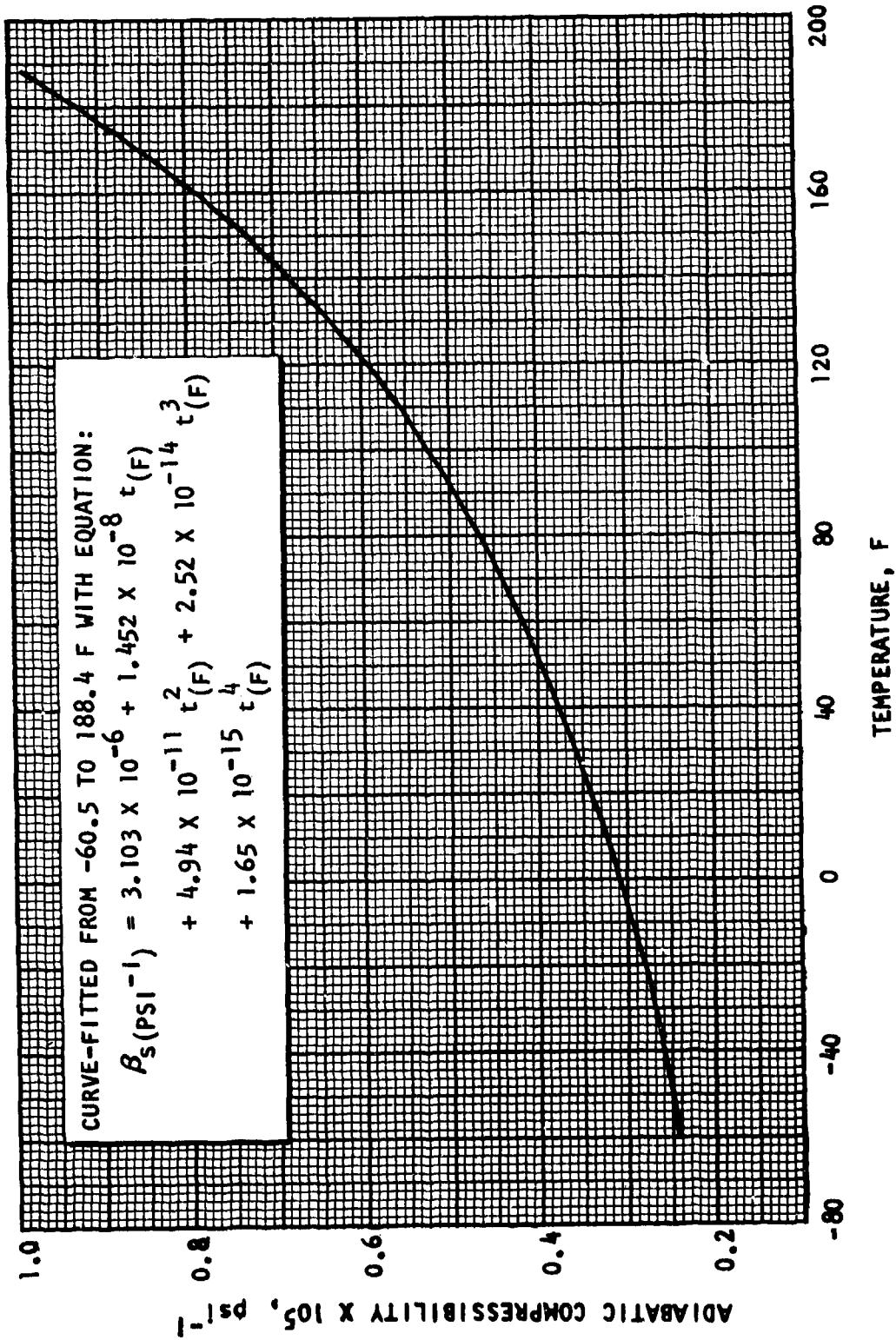


Figure C-3a. Adiabatic Compressibility of MON-25 (Ref. C-11)

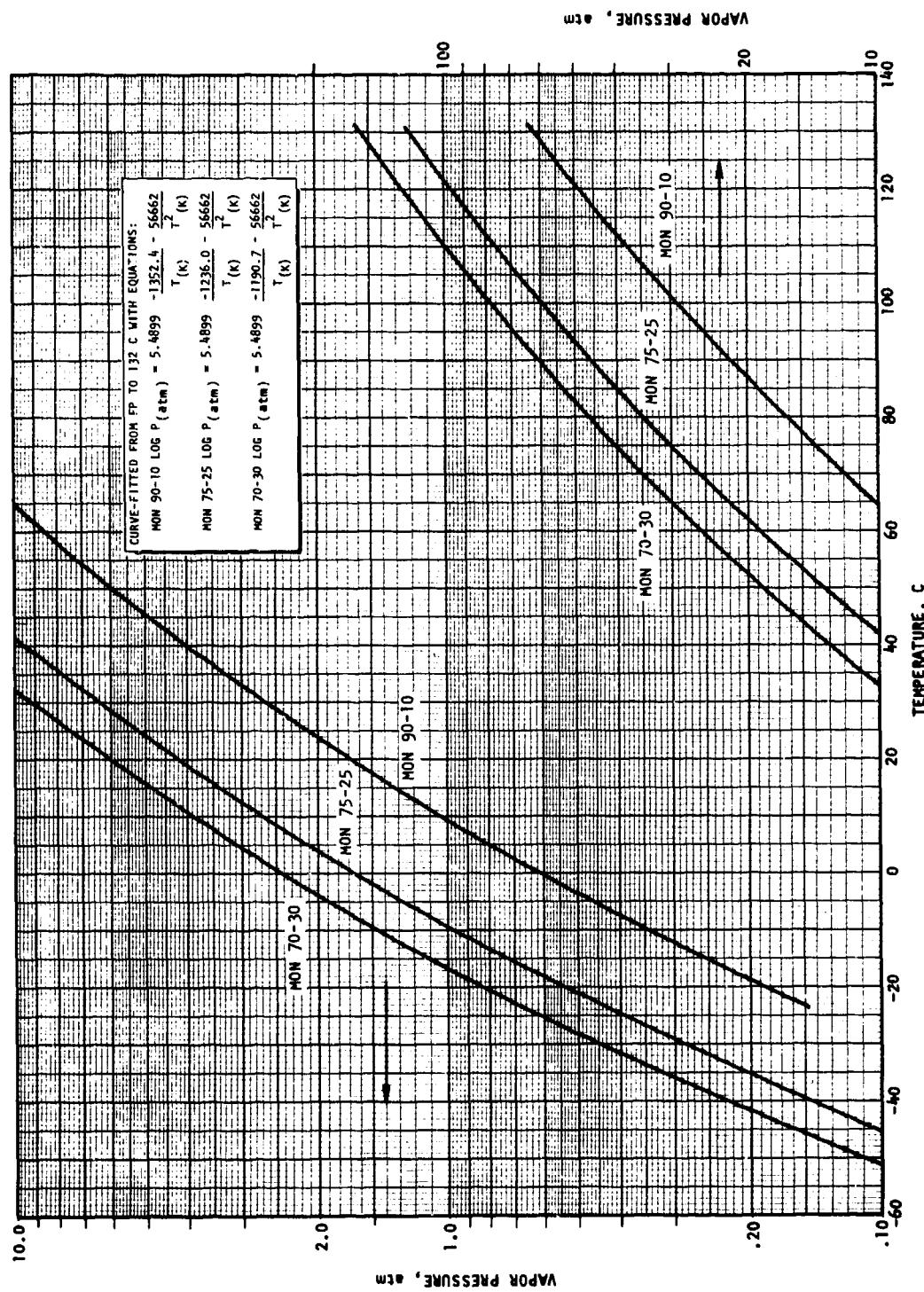


Figure C-4. Vapor Pressure of the Mixed Oxides of Nitrogen (Ref. C-2, C-4, C-7, and C-10)

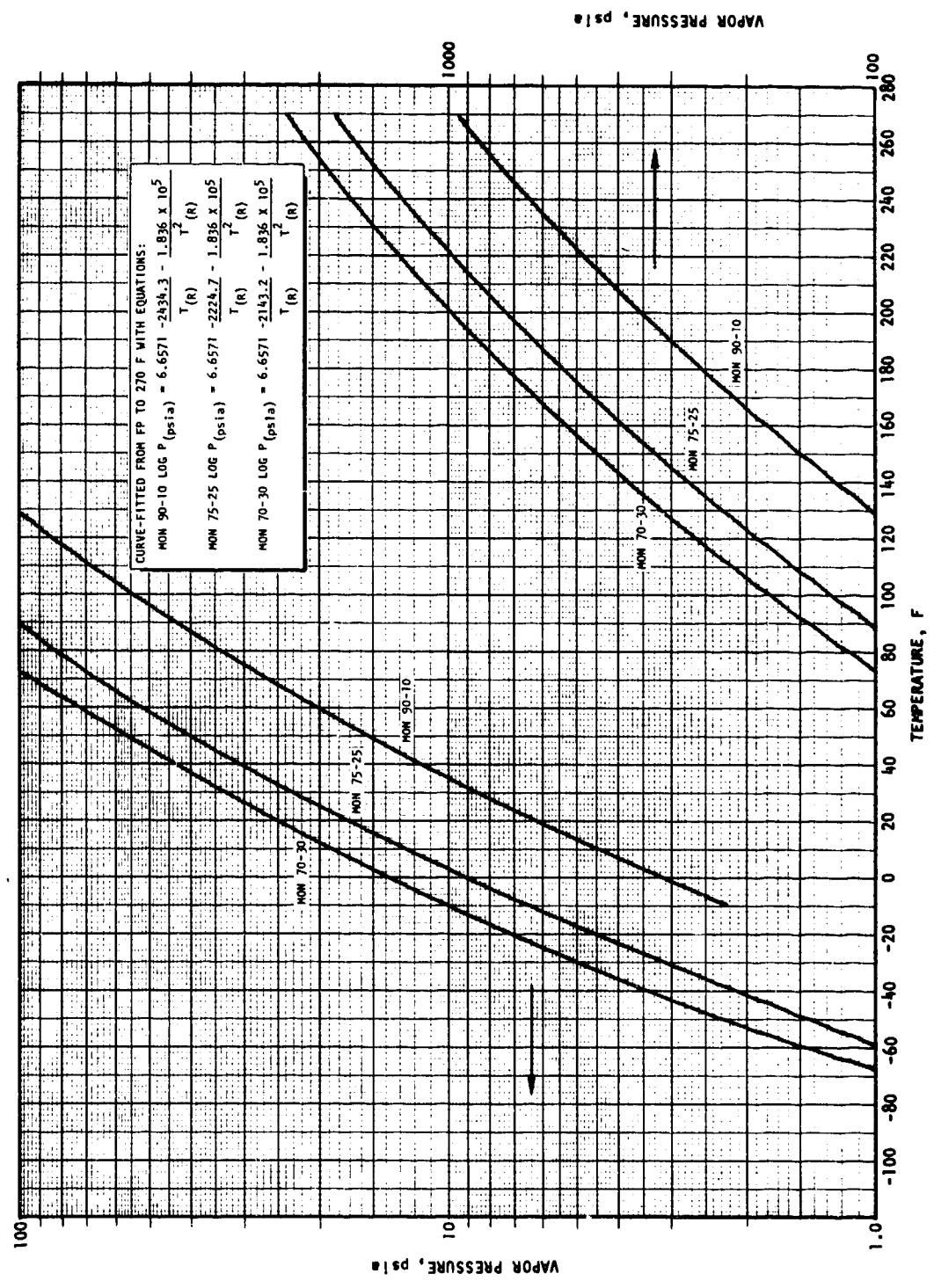


Figure 4a. Vapor Pressure of the Mixed Oxides of Nitrogen
(Ref. C-2, C-4, C-7, and C-10)

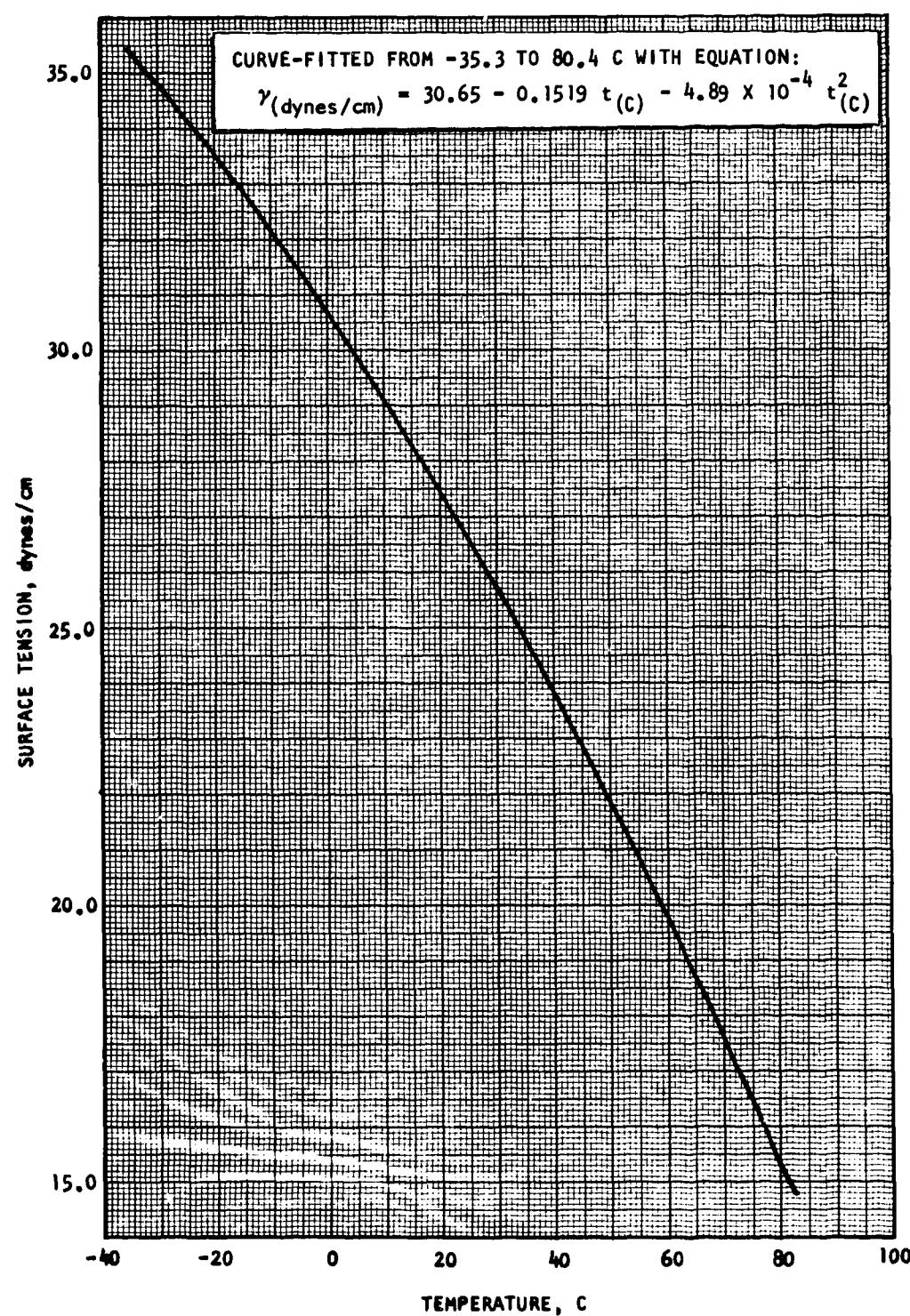


Figure C-5. Surface Tension of Saturated Liquid MON-25 (Ref. C-11)

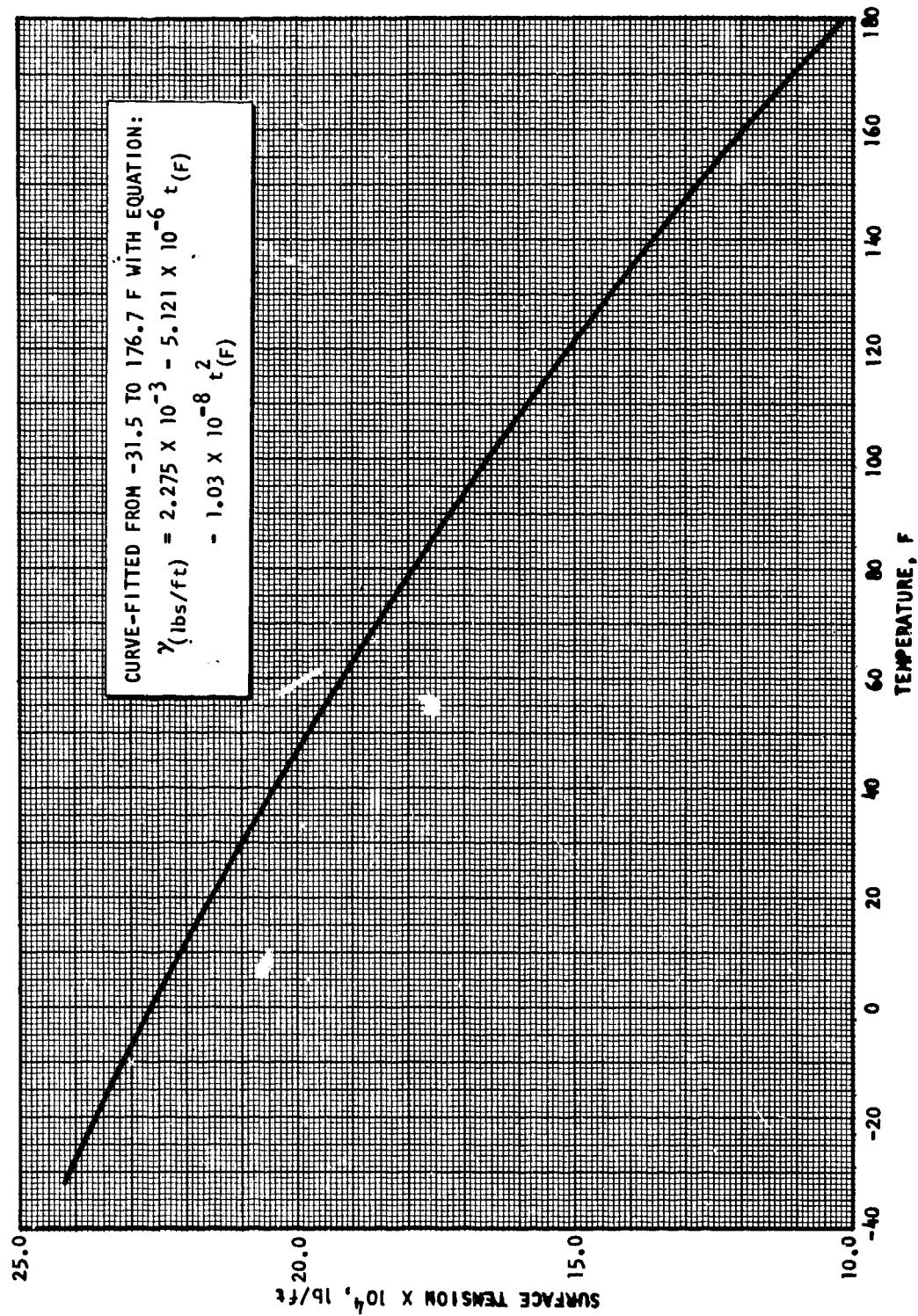


Figure C-5a. Surface Tension of Saturated Liquid MON-25 (Ref. C-11)

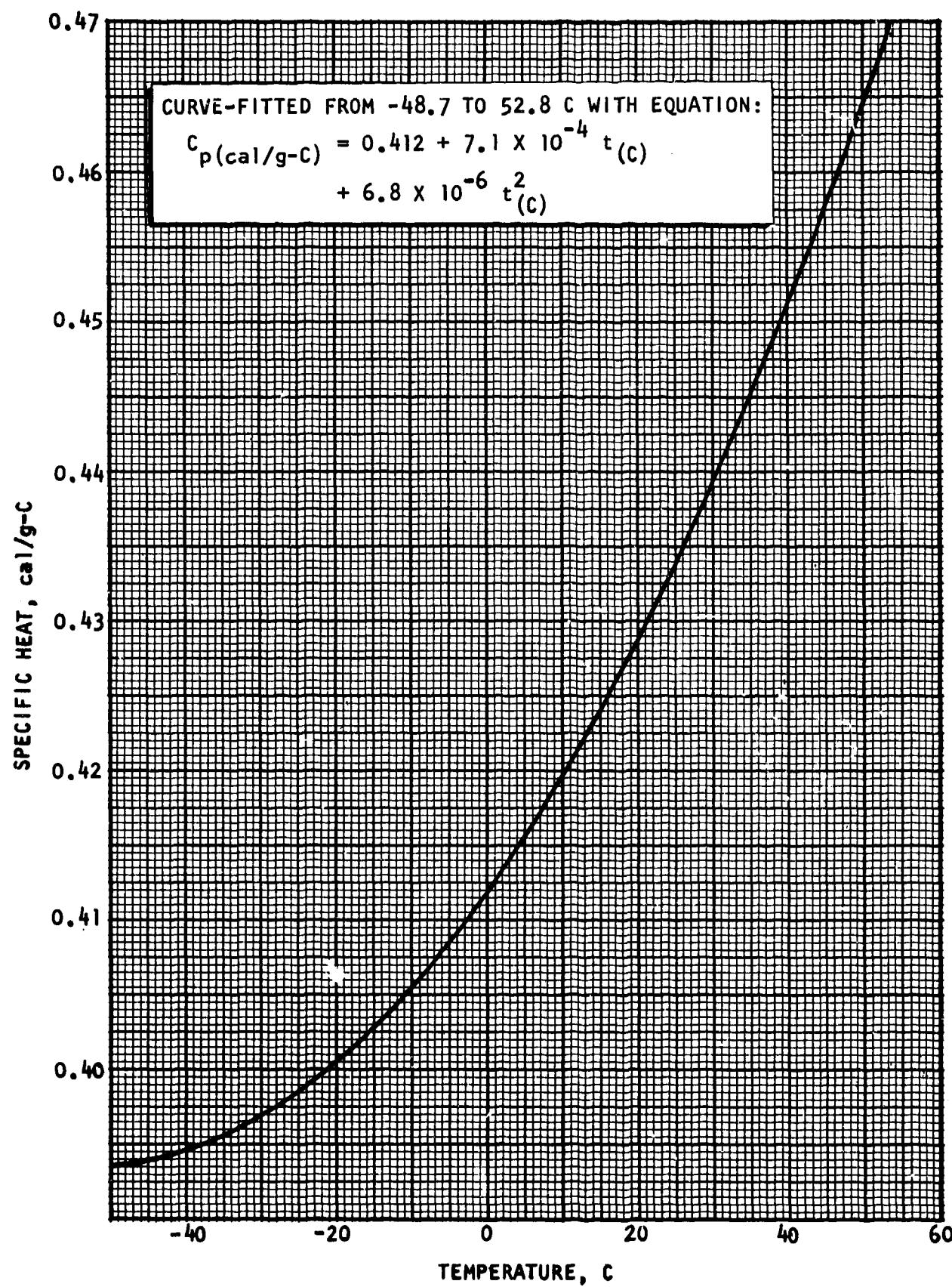


Figure C-6. Specific Heat of Saturated Liquid MON-25 (Ref. C-11)

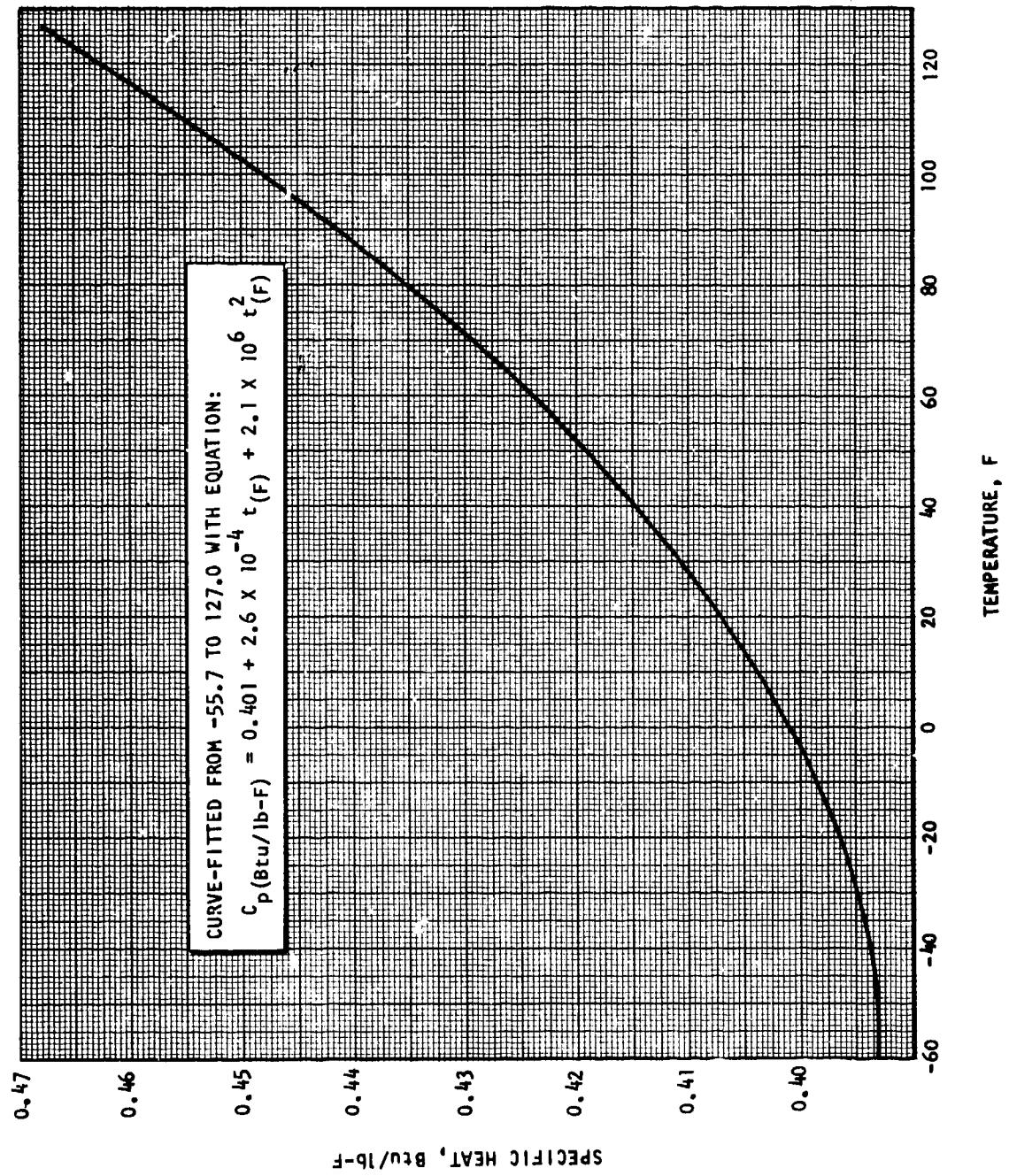


Figure C-6a. Specific Heat of Saturated Liquid MON-25 (Ref. C-11)

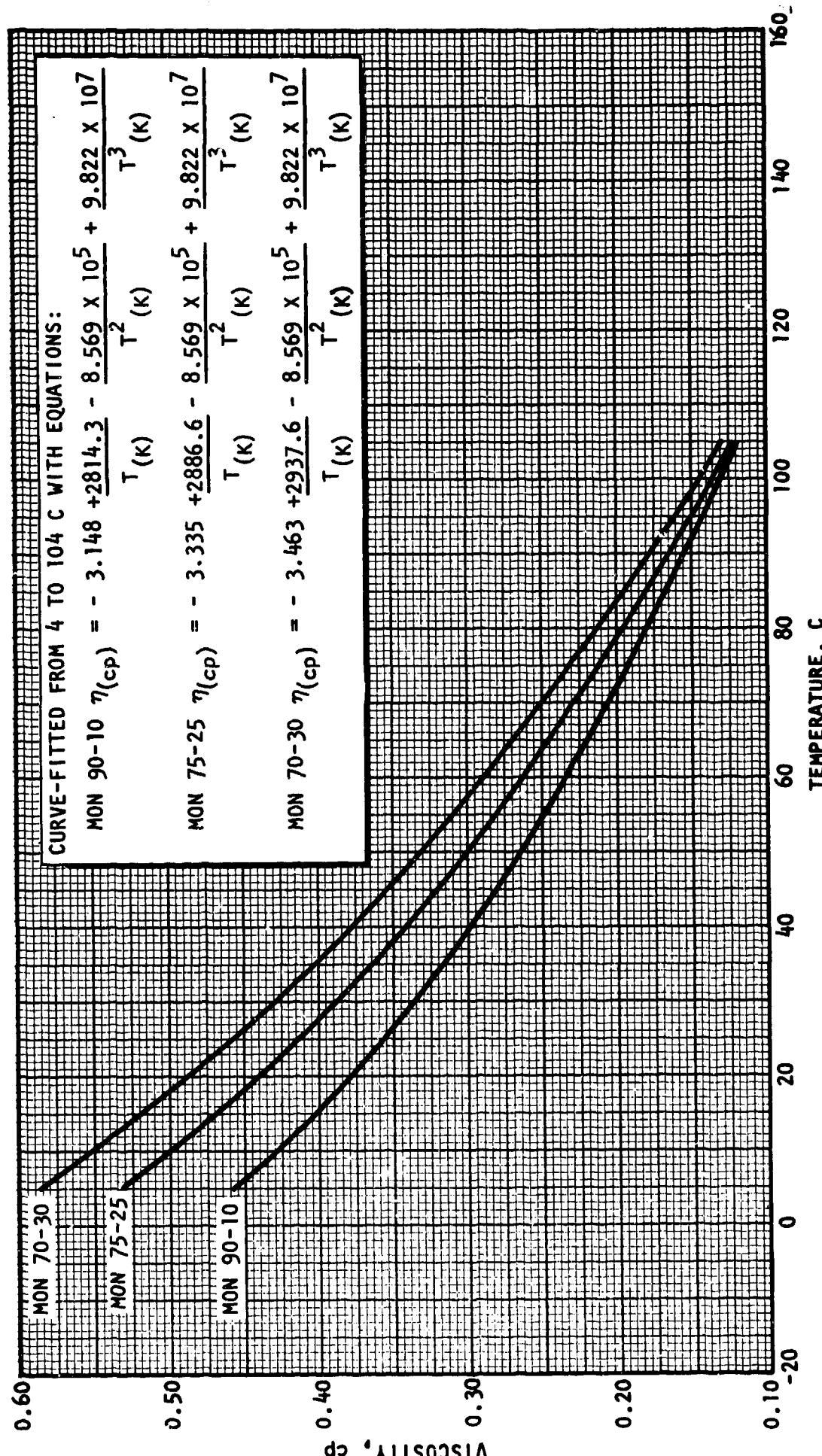


Figure C-7. Viscosity of the Mixed Oxides of Nitrogen (Ref. C-14)

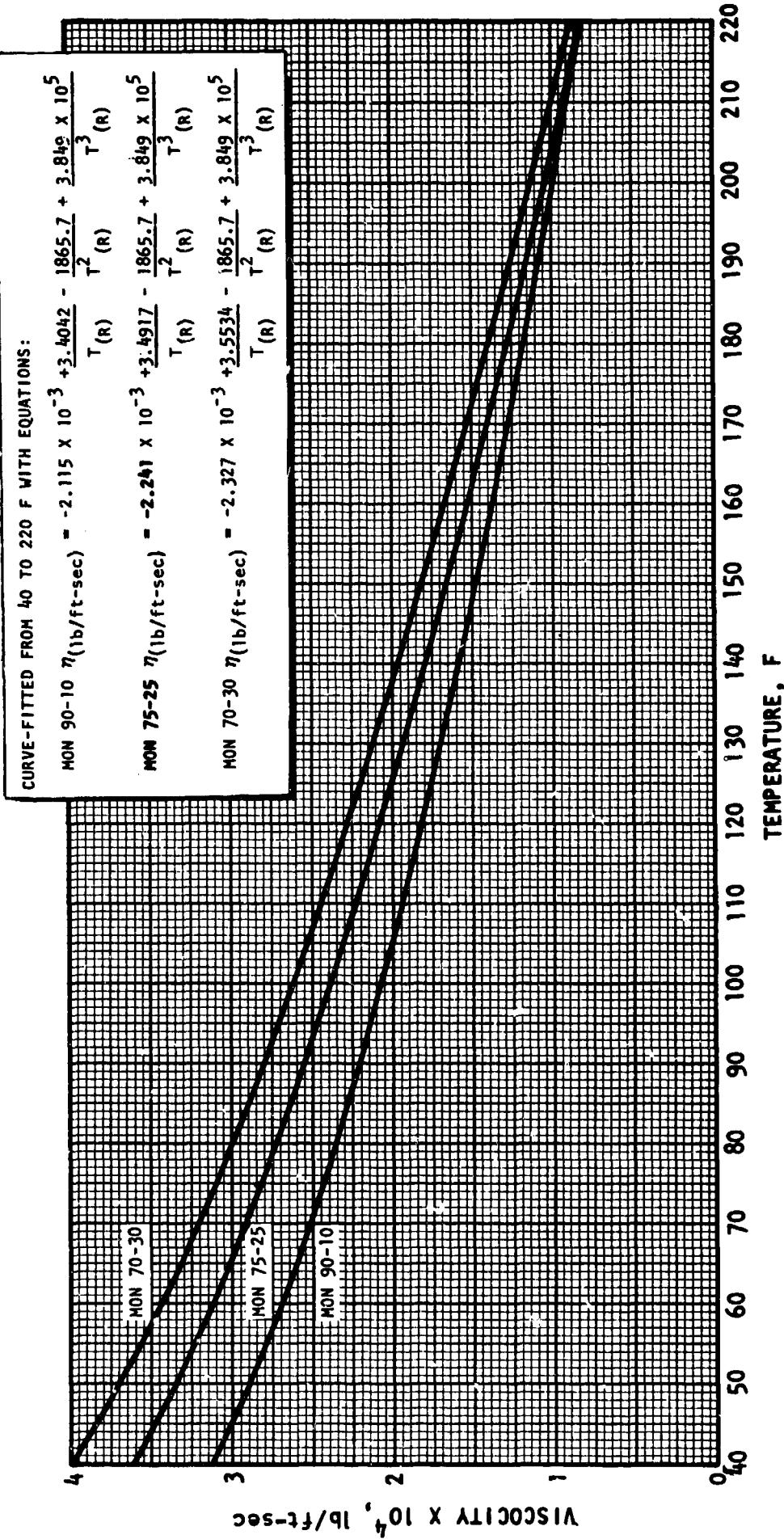


Figure C-7a. Viscosity of the Mixed Oxides of Nitrogen (Ref. C-14)

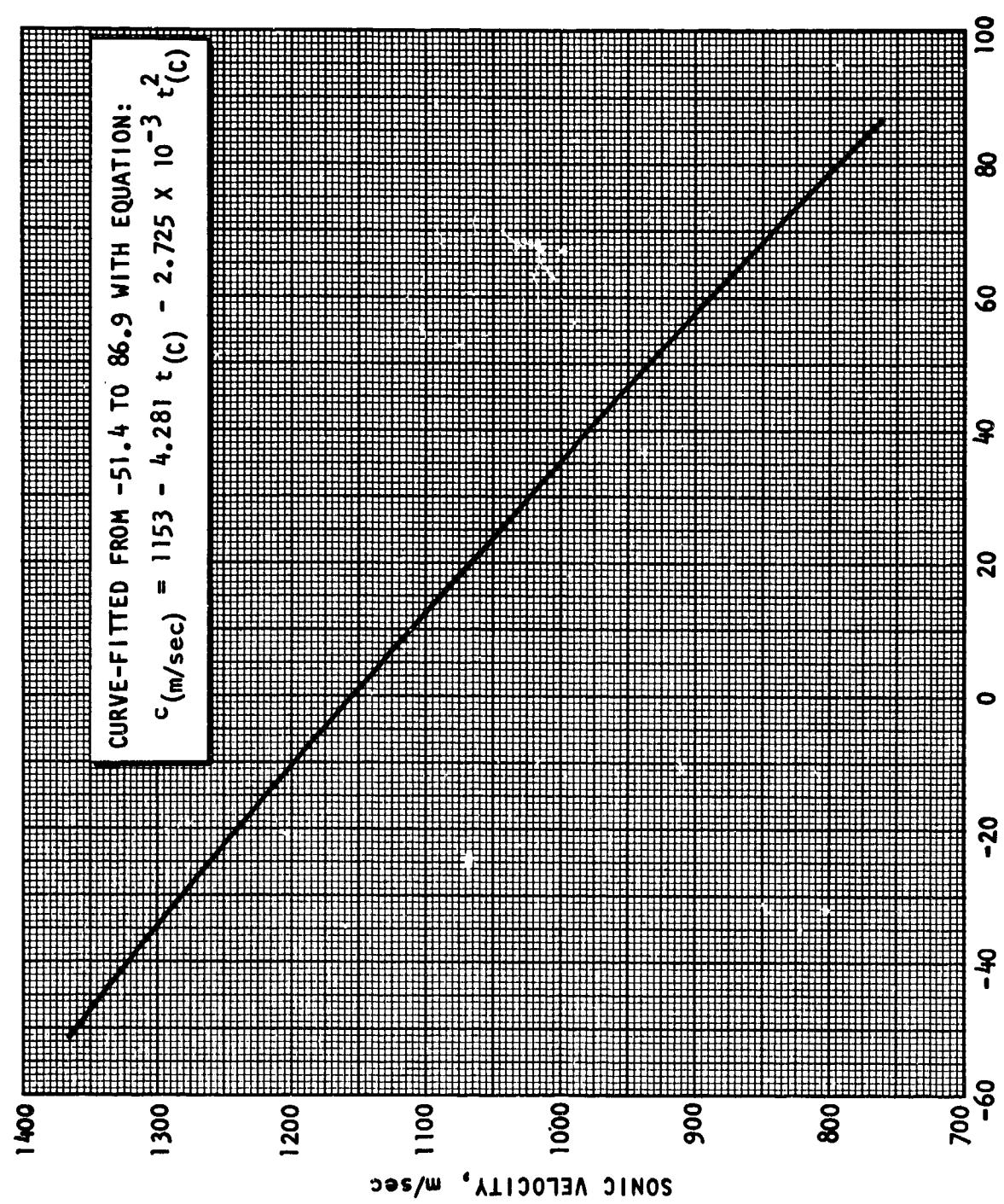


Figure C-8. Sonic Velocity in Saturated Liquid MON-25 (Ref. C-11)

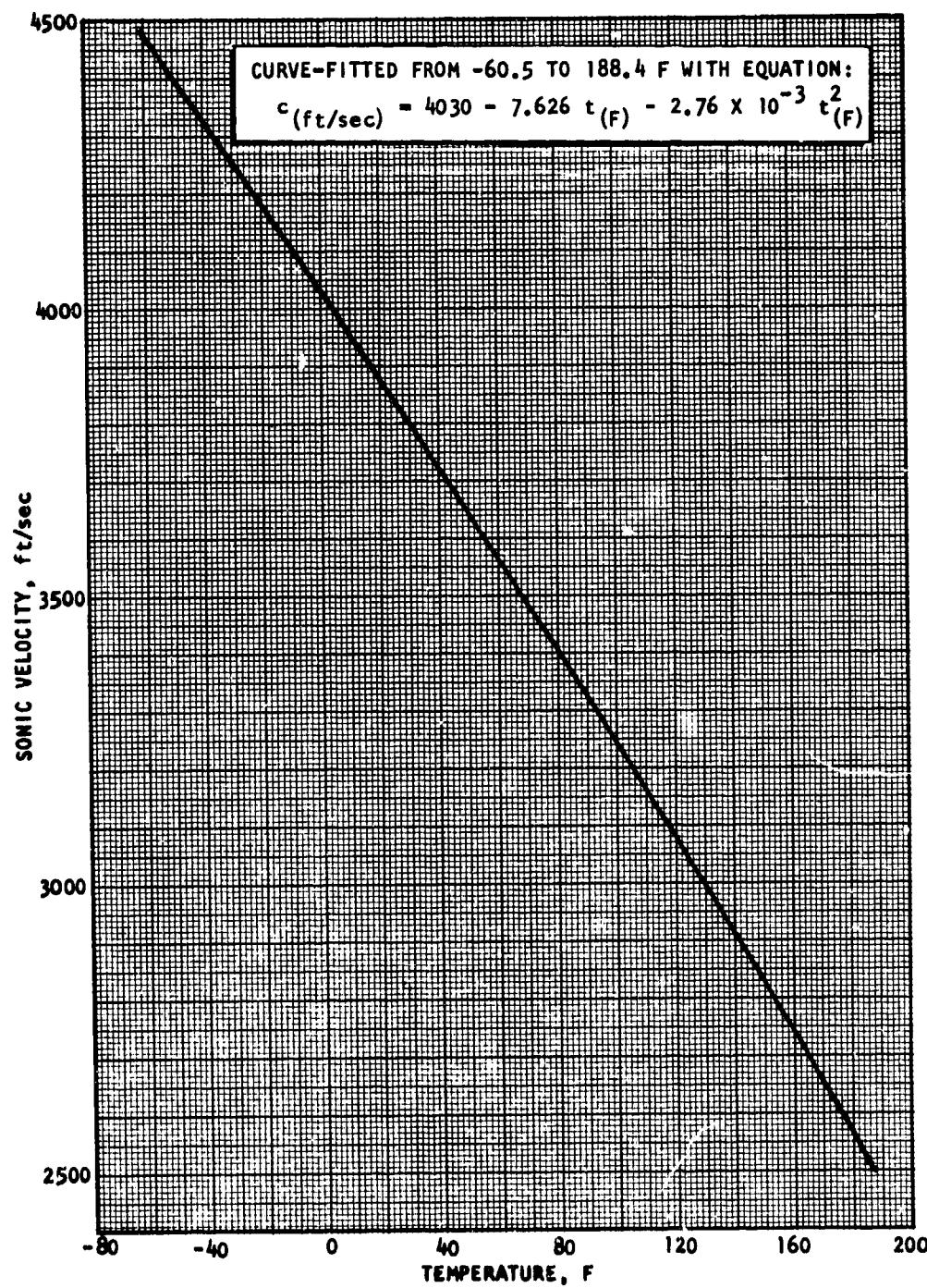


Figure C-8a. Sonic Velocity in Saturated Liquid MON-25 (Ref. C-11)

APPENDIX D

SELECTED PHYSICAL PROPERTIES OF THE FUMING NITRIC ACIDS

(U) Correlations of the densities, vapor pressures, and viscosities of the white fuming nitric acid (WFNA), red fuming nitric acid (RFNA), and maximum density fuming nitric acid (MDFNA) as a function of temperature and composition are given in Tables D-1, D-2, and D-3, respectively. These correlations are least squares curve-fits of the experimental data given in Ref. D-1 through D-12.

TABLE D-1
DENSITIES OF THE FUMING NITRIC ACIDS

Formulation	Composition Range	Temperature Range	Equation (1)	Standard Error of Estimate	Referenced Data (2)
WPA	0 to 5 w/o N_2O_4 (N) 0 to 5 w/o H_2O (N) 90 to 100 w/o HNO_3	0 to 105 C	$\rho(\text{kg/cc}) = 1.5450 - 1.754 \times 10^{-3}t_{(C)} + 4.49 \times 10^{-3}N_{(w/o)} - 3.59 \times 10^{-3}N_{(w/o)}^2$	0.0027 g/cc	D-1, -2, -3, -4, -5
		32 to 221 F	$\rho(\text{lb/cu-ft}) = 98.38 - 6.013 \times 10^{-2}t_{(F)} + 0.281 N_{(w/o)} - 0.224 N_{(w/o)}^2$	0.17 lb/cu-ft	
RPA	8 to 20 w/o N_2O_4 (N) 0 to 6 w/o H_2O (N) 72 to 92 w/o HNO_3	0 to 40 C	$\rho(\text{kg/cc}) = 1.5340 - 1.656 \times 10^{-3}t_{(C)} + 6.06 \times 10^{-3}N_{(w/o)} - 3.05 \times 10^{-3}N_{(w/o)}^2$ - 7.92 $\times 10^{-5}N_{(w/o)}^2$ - 1.13 $\times 10^{-1}N_{(w/o)}^3$	0.0021 g/cc	D-2, -3, -4, -5
		32 to 104 F	$\rho(\text{lb/cu-ft}) = 97.65 - 5.87 \times 10^{-2}t_{(F)} + 0.378 N_{(w/o)} - 0.190 N_{(w/o)}^2$ - 4.95 $\times 10^{-3}N_{(w/o)}^2$ - 7.1 $\times 10^{-5}N_{(w/o)}^3$	0.13 lb/cu-ft	
MPNA (3)	75 to 50 w/o N_2O_4 (N) 0 to 5 w/o H_2O (N) 49 to 65 w/o HNO_3	0 to 21 C	$\rho(\text{kg/cc}) = 1.4872 - 1.045 \times 10^{-3}t_{(C)} + 8.557 \times 10^{-3}N_{(w/o)} - 8.2 \times 10^{-3}N_{(w/o)}^2$ - 9.68 $\times 10^{-5}N_{(w/o)}^2$ - 1.88 $\times 10^{-5}N_{(w/o)}^3$	0.0021 g/cc	D-2, -3, -6
		32 to 69 F	$\rho(\text{lb/cu-ft}) = 94.01 - 3.617 \times 10^{-2}t_{(F)} + 0.5558 N_{(w/o)} - 5.1 \times 10^{-2}N_{(w/o)}^2$ - 6.04 $\times 10^{-3}N_{(w/o)}^2$ - 6.52 $\times 10^{-4}N_{(w/o)}^3$	0.13 lb/cu-ft	
			$N_{(w/o)} = 44.08 - 0.0971 t_{(C)}$	1.27 N	

(1) At physical equilibrium, not at chemical equilibrium.

(2) The high temperature data of Reamer and Sage (Ref. D-15 through D-17) was not used in the correlations since it was incompatible with the low temperature data from the other sources and internally inconsistent. The Reamer and Sage data suggest that density is a more or less random function of N_{2O_4} concentration.

(3) The weight percent N_2O_4 (N) required for maximum density nitric acid from the indicated equations and $dn/dN = 0$ is:

$$N_{(w/o)} = 44.08 - 0.0971 t_{(C)} - 1.27 N$$

TABLE D-2
VAPOR PRESSURES OF THE FUMING NITRIC ACIDS

Formulation	Composition Range	Temperature Range	Equation (1)	Equation (1)	Standard Error of Estimate	Referenced Data (2)
WFNA	0 to 3 w/o N_2O_4 (N) 0 to 6 w/o H_2O (H) 94 to 100 w/o HNO_3	10 to 100 C	$\log_{10} P \text{ (paia)} = 5.560 + 0.285 \ln \left(\frac{w}{o} \right) + 1.61 \times 10^{-3} N \left(\frac{w}{o} \right)^2 - 1.20 \times 10^{-2} N \left(\frac{w}{o} \right)^3 - 1.982 \frac{N^2}{T} - 21.20 \frac{N}{T} \left(\frac{w}{o} \right)$	$\log_{10} P \text{ (paia)} = 5.560 + 0.285 \ln \left(\frac{w}{o} \right) + 1.61 \times 10^{-3} N \left(\frac{w}{o} \right)^2 - 1.20 \times 10^{-2} N \left(\frac{w}{o} \right)^3 - 1.982 \frac{N^2}{T} - 21.20 \frac{N}{T} \left(\frac{w}{o} \right)$	3.4% in P	D-7, -8
RFNA	10 to 17 w/o N_2O_4 (N) 1 to 6 w/o H_2O (H) 77 to 86 w/o HNO_3	50 to 212 F	$\log_{10} P \text{ (paia)} = 6.747 + 0.285 \ln \left(\frac{w}{o} \right) + 1.61 \times 10^{-3} N \left(\frac{w}{o} \right)^2 - 1.20 \times 10^{-2} N \left(\frac{w}{o} \right)^3 - 2529.2 \frac{N^2}{T} - 1.2820 \frac{N}{T} \left(\frac{w}{o} \right)$	$\log_{10} P \text{ (paia)} = 6.747 + 0.285 \ln \left(\frac{w}{o} \right) + 1.61 \times 10^{-3} N \left(\frac{w}{o} \right)^2 - 1.20 \times 10^{-2} N \left(\frac{w}{o} \right)^3 - 2529.2 \frac{N^2}{T} - 1.2820 \frac{N}{T} \left(\frac{w}{o} \right)$		
MDNA	39 to 51 w/o N_2O_4 (N) 1.4 to 2.4 w/o H_2O (H) 47 to 60 w/o HNO_3	10 to 57 C 50 to 135 F	$\log_{10} P \text{ (paia)} = -6.447 - 2.24 \times 10^{-2} N \left(\frac{w}{o} \right)^2 + 1.72 \times 10^{-3} N \left(\frac{w}{o} \right)^3 - 2250.5 \frac{N^2}{T} + 13.58 \frac{N}{T} \left(\frac{w}{o} \right)$ $\log_{10} P \text{ (paia)} = -7.644 - 2.24 \times 10^{-2} N \left(\frac{w}{o} \right)^2 + 1.72 \times 10^{-3} N \left(\frac{w}{o} \right)^3 - 4050.8 \frac{N^2}{T} + 24.38 \frac{N}{T} \left(\frac{w}{o} \right)$	$\log_{10} P \text{ (paia)} = -6.447 - 2.24 \times 10^{-2} N \left(\frac{w}{o} \right)^2 + 1.72 \times 10^{-3} N \left(\frac{w}{o} \right)^3 - 2250.5 \frac{N^2}{T} + 13.58 \frac{N}{T} \left(\frac{w}{o} \right)$ $\log_{10} P \text{ (paia)} = -7.644 - 2.24 \times 10^{-2} N \left(\frac{w}{o} \right)^2 + 1.72 \times 10^{-3} N \left(\frac{w}{o} \right)^3 - 4050.8 \frac{N^2}{T} + 24.38 \frac{N}{T} \left(\frac{w}{o} \right)$	2.8% in P	D-9
			$\log_{10} P \text{ (paia)} = 9.355 - 1.504 \times 10^{-2} N \left(\frac{w}{o} \right) - 0.5926 \frac{N^2}{T} \left(\frac{w}{o} \right) - 8.47210^{-3} N \left(\frac{w}{o} \right)^2 - 2501.2 + 21.07 N \left(\frac{w}{o} \right) - 173.1 \frac{N}{T} \left(\frac{w}{o} \right)$	$\log_{10} P \text{ (paia)} = 9.355 - 1.504 \times 10^{-2} N \left(\frac{w}{o} \right) - 0.5926 \frac{N^2}{T} \left(\frac{w}{o} \right) - 8.47210^{-3} N \left(\frac{w}{o} \right)^2 - 2501.2 + 21.07 N \left(\frac{w}{o} \right) - 173.1 \frac{N}{T} \left(\frac{w}{o} \right)$	4.8% in P	D-10
		14 to 50 F	$\log_{10} P \text{ (paia)} = 10.522 - 1.504 \times 10^{-2} N \left(\frac{w}{o} \right) - 0.5926 \frac{N^2}{T} \left(\frac{w}{o} \right) - 8.47210^{-3} N \left(\frac{w}{o} \right)^2 - 392.1 + 25.32 N \left(\frac{w}{o} \right) + 511.6 \frac{N}{T} \left(\frac{w}{o} \right)$	$\log_{10} P \text{ (paia)} = 10.522 - 1.504 \times 10^{-2} N \left(\frac{w}{o} \right) - 0.5926 \frac{N^2}{T} \left(\frac{w}{o} \right) - 8.47210^{-3} N \left(\frac{w}{o} \right)^2 - 392.1 + 25.32 N \left(\frac{w}{o} \right) + 511.6 \frac{N}{T} \left(\frac{w}{o} \right)$		

(1) At physical equilibrium, not at chemical equilibrium.

(2) The high temperature data of Reamer and Sage (Ref. D-14, -15) could not be used since it was obtained for the system at chemical equilibrium. A correlation for the system at chemical equilibrium could not be obtained since the data was too inconsistent. Pressure was a very irregular, but generally inverse function of N_2O_4 content.

TABLE D-3
VISCOSITIES OF THE FUMING NITRIC ACIDS

Formulation	Composition Range	Temperature Range	Equation (1)	Standard Error of Estimate	Referenced Data
WFNA	0 to 5 v/o N_2O_4 (N) 0 to 5 v/o H_2O (H) 90 to 100 v/o HNO_3	0 to 71 C	$\log_{10} \eta_{(ep)} = 1.761 - 0.0643N(v/o) - 0.0241N(v/o)^2 - 5 \times 10^{-3}N(v/o)^3 - 2.95 \times 10^{-5}N(v/o)^4 + 4.90 \cdot 2 \cdot 10^{-6}N(v/o)^5 - \frac{10.8N(v/o)}{T(K)}$	2.4% in η	D-5, 11
		32 to 160 F	$\log_{10} \eta_{(lb/ft-sec)} = -4.573 - 0.0643N(v/o) - 0.0241N(v/o)^2 - 5 \times 10^{-3}N(v/o)^3 - 2.95 \times 10^{-5}N(v/o)^4 + 4.90 \cdot 2 \cdot 10^{-6}N(v/o)^5 - \frac{10.8N(v/o)}{T(R)}$ + $\frac{19.3N(v/o)}{T(R)}$		
RFNA	11 to 20 v/o N_2O_4 (N) 0 to 6 v/o H_2O (H) 76 to 89 v/o HNO_3	0 to 116 C	$\log_{10} \eta_{(ep)} = -5.262 - 0.1083N(v/o) - 2.66 \times 10^{-2}N(v/o)^2 - 6.02 \times 10^{-5}N(v/o)^3 - 1.673 \cdot 2 \cdot 10^{-7}N(v/o)^4 + 11.1N(v/o)^5 - \frac{14.8750}{T(K)}$	3.8% in η	D-5, 11
		32 to 240 F	$\log_{10} \eta_{(lb/ft-sec)} = -6.435 - 0.1083N(v/o) - 2.66 \times 10^{-2}N(v/o)^2 + 3.602 \times 10^{-5}N(v/o)^3 + 120.8 \cdot 2 \cdot 10^{-8}N(v/o)^4 - \frac{182000}{T(R)}$		
MDFNA	25 to 53 v/o N_2O_4 (N) 0 to 6 v/o H_2O (H) 47 to 53 v/o HNO_3	0 to 20 C	$\log_{10} \eta_{(ep)} = -2.804 + 2.250 \times 10^{-2}N(v/o) - 4.969 \times 10^{-4}N(v/o)^2 - 5.4 \times 10^{-7}N(v/o)^3 - 2.026 \times 10^{-10}N(v/o)^4 - \frac{647.5 \cdot 6.52N(v/o)}{T(K)}$ + $\frac{20.26N(v/o)}{T(K)}$	2.1% in η	D-5, 12
		32 to 68 F	$\log_{10} \eta_{(lb/ft-sec)} = -5.977 + 2.250 \times 10^{-2}N(v/o) - 4.969 \times 10^{-4}N(v/o)^2 - 5.4 \times 10^{-7}N(v/o)^3 - 2.026 \times 10^{-10}N(v/o)^4 - \frac{647.5 \cdot 6.52N(v/o)}{T(R)}$ + $\frac{11.72N(v/o) + 36.4N(v/o)}{T(R)}$		

(1) At physical equilibrium, not at chemical equilibrium.

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APPENDIX E

PHYSICAL PROPERTIES OF FLOROX

(U) The physical and thermodynamic properties of Florox are presented in Table E-1. Figures E-1 through E-7a are graphical illustrations of the properties listed in Table E-1.

E-1

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TABLE E-1
PHYSICAL PROPERTIES OF FLOROX AT 25 C (77 F)

Property	Value		Figure Number	Reference Number
	Metric	English		
General Identification				
Identification	Oxychlorine trifluoride, Florox			
Molecular Formula	ClF ₃ ⁰			
Molecular Weight*	108.448 g/g-mole	108.448 lb/lb-mole		
Melting Point	-41.7 C	-43 F		E-1
Triple Point	-41.8 C	-43.2 F		E-2
Normal Boiling Point	30.6 C	87.1 F		E-3
Critical Properties				
Temperature				
Pressure				
Density				
Volume				
Phase Properties				
Density				
Solid				
Liquid				
Gas				

*Calculated data.

E-2

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TABLE E-1
PHYSICAL PROPERTIES OF FLOROX AT 25 C (77 F)
(Continued)

Property	Metric	Value	Figure Number	Reference Number
		English		
Thermal Expansion (cubic)				
Compressibility	$7.937 \times 10^{-5} \text{ atm}^{-1}$	$5.401 \times 10^{-6} \text{ psi}^{-1}$	E-2, -2a	E-3
Adiabatic Isothermal				
Vapor Pressure	0.80 atm	11.74 psia	E-3, -3a	E-3
Surface Tension				
Inert-Gas Solubility				
<u>Thermodynamic Properties</u>				
Heats of				
Formation (liquid)	$-39.6 \pm 1.7 \text{ Kcal/mole}$	-657.2 Btu/lb	E-4	
Fusion	$1.05 \pm 0.10 \text{ Kcal/mole}$ at MP	17.4 Btu/lb at MP	E-5	
Vaporization**	7.0 Kcal/mole of NBP	116.2 Btu/lb at NBP	E-3	
Heat Capacity				
Solid				
Liquid	0.3113 cal/g-C	0.3113 Btu/lb-F	E-4, -4a	E-3
Gas				

**Calculated from vapor pressure equation.

E-3

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TABLE E-1
PHYSICAL PROPERTIES OF FLOROX AT 25 C (77 F)
(Continued)

Property	Value		Figure Number	Reference Number
	Metric	English		
Entropy				
Enthalpy				
<u>Transport Properties</u>				
Viscosity				
Liquid	0.618 cp	4.15×10^{-4} lb/ft sec	E-5,-5a	E-3
Gas				
Thermal Conductivity				
Liquid	4.051×10^{-4} cal/cm-sec-C	0.0980 Btu/ft-hr-F	E-6	E-3
Gas				
Sonic Velocity				
Liquid	830.1 m/sec	2723.5 ft/sec	E-7,-7a	E-3
Gas				
<u>Electromagnetic Properties</u>				
Index of Refraction				
Liquid				
Gas				
Dipole Moment				

E-4

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TABLE E-1
PHYSICAL PROPERTIES OF FLOROX AT 25 C (77 F)
(Concluded)

Property	Value		Figure Number	Reference Number
	Metric	English		
Dielectric Constant				
Liquid				
Gas	$\sim 2 \times 10^{-8}$	$\text{ohms}^{-1} \text{ cm}^{-1}$		
Electrical Conductivity				
Magnetic Susceptibility				E-6

General Description

Appearance: Florox is a colorless water-white, mobile liquid, which freezes to a white solid. Vapor density measurements show the molecule to be monomeric in the vapor phase, although the high-density normal boiling point and Trouton constant indicate a fairly associated liquid.

Odor: Characteristic irritating, pungent odor

Toxicity: Threshold Limit Value (TLV) = 0.1 ppm (same as for ClF_3)

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REFERENCES

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- E-2. Rocketdyne, A Division of North American Rockwell Corporation, Canoga Park, California, Production of a Packageable Oxidizer, Final Report No. R-7755, Contract N00019-68-C-0332, January 1969, CONFIDENTIAL.
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- E-4. The Dow Chemical Company, Midland, Michigan, The Heat of Formation of Propellant Ingredients, Special Report No. AFRPL-TR-67-311, Contract F04611-67-C-0009, December 1967, CONFIDENTIAL.
- E-5. Rocketdyne, A Division of North American Aviation, Inc., Canoga Park, California, Verification of a New Liquid Oxidizer, Report No. R-7034, Contract N0w66-0639-d, May 1967, CONFIDENTIAL.
- E-6. Rocketdyne, A Division of North American Aviation, Inc., Canoga Park, California, Inorganic Halogen Oxidizers, Final Report No. R-7149, Contract N0Nr-4428(00), July 1967, CONFIDENTIAL.

E-6

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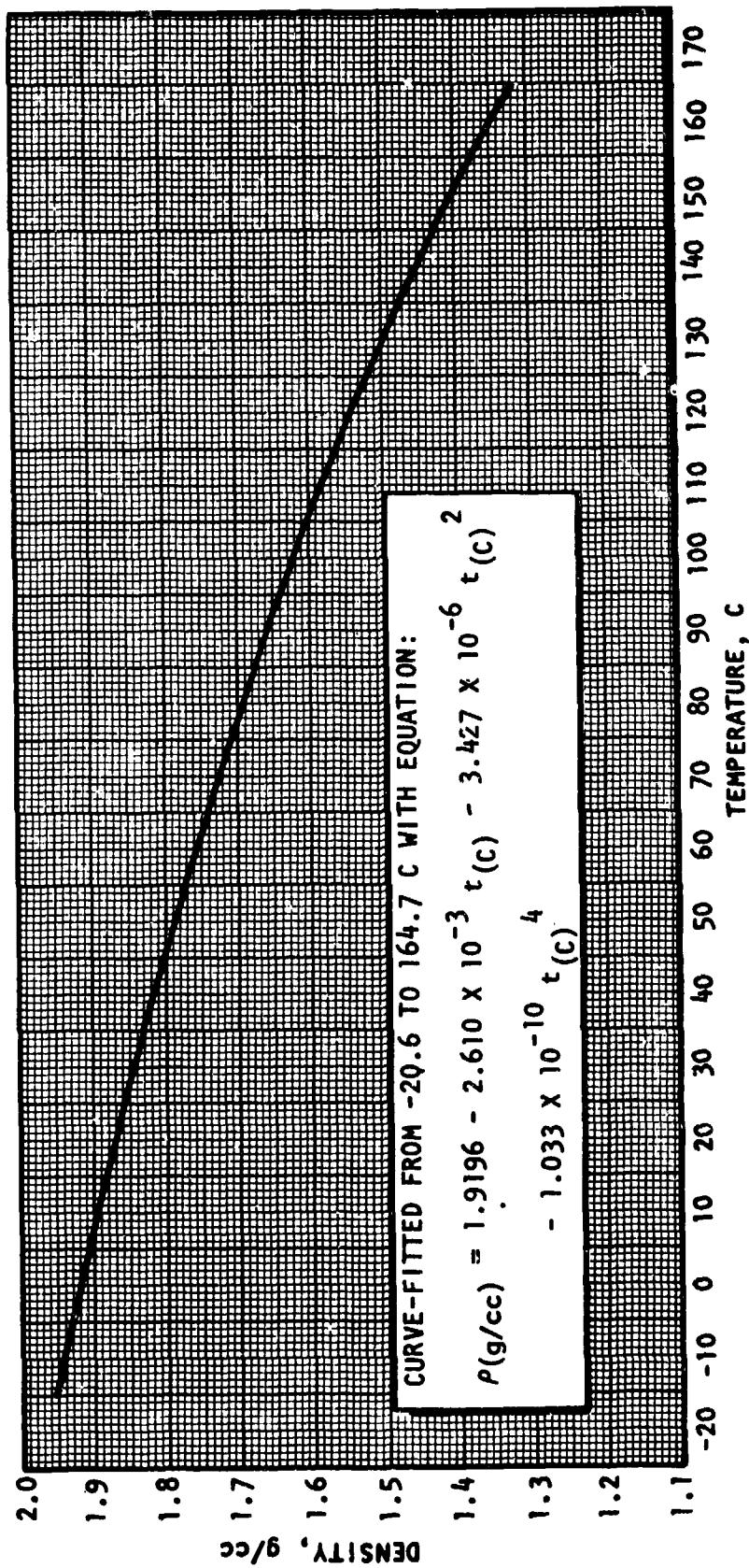


Figure E-1. Density of Saturated Liquid Flurox (Ref. E-3)

E-7

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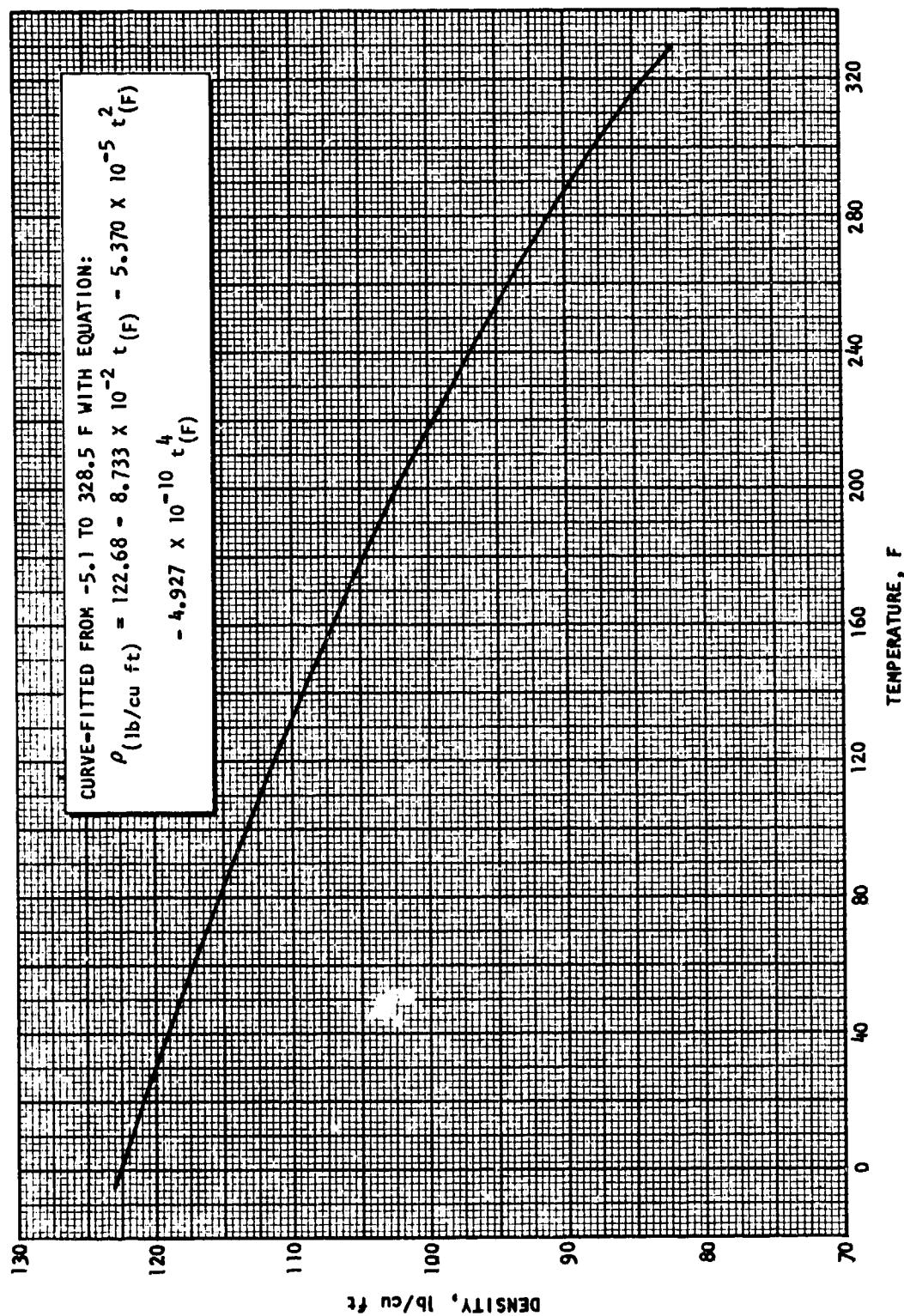


Figure E-1a. Density of Saturated Liquid Fluorox (Ref. E-3)

E-8
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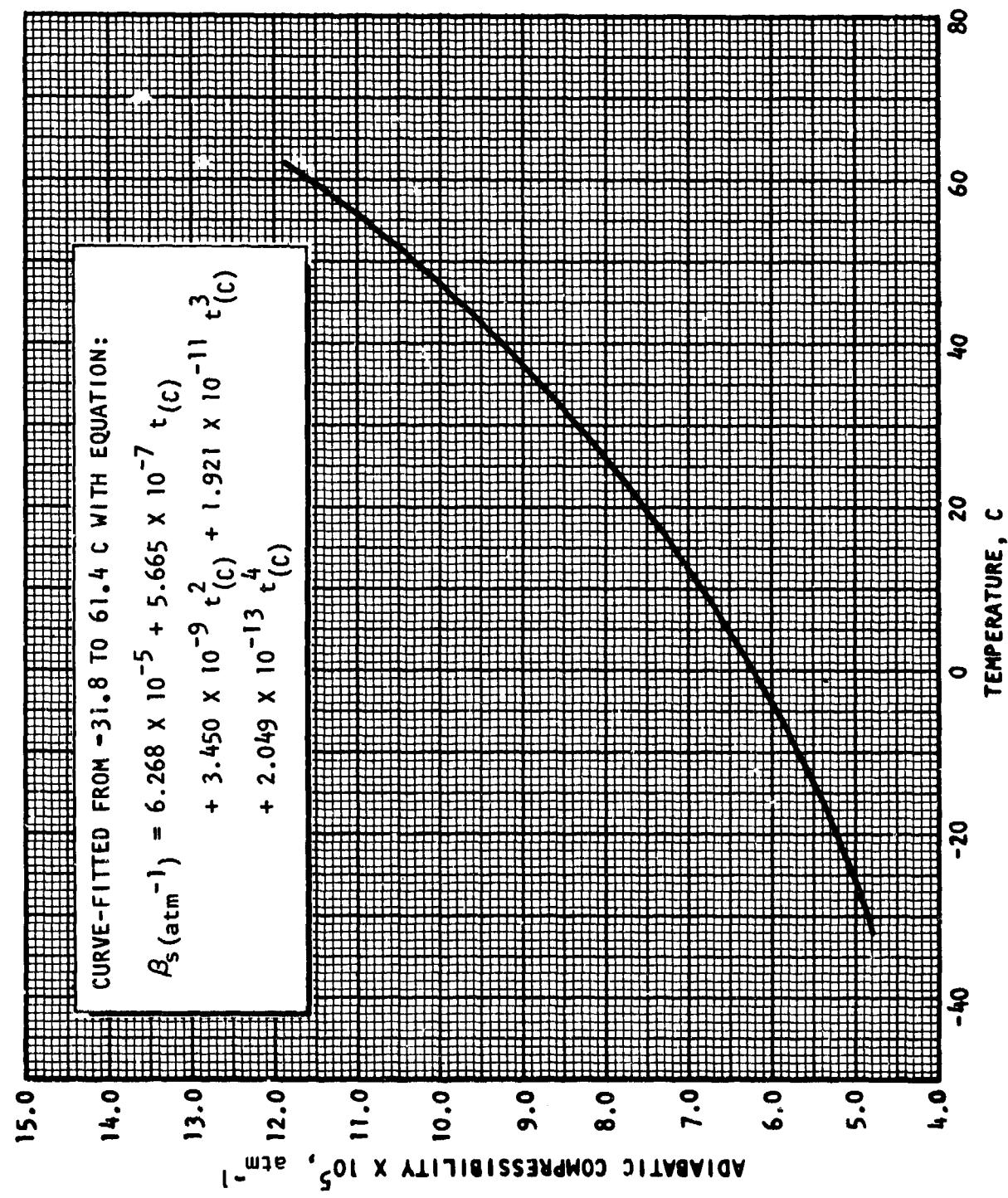


Figure E-2. Adiabatic Compressibility of Fluorox (Ref. E-3)

E-9

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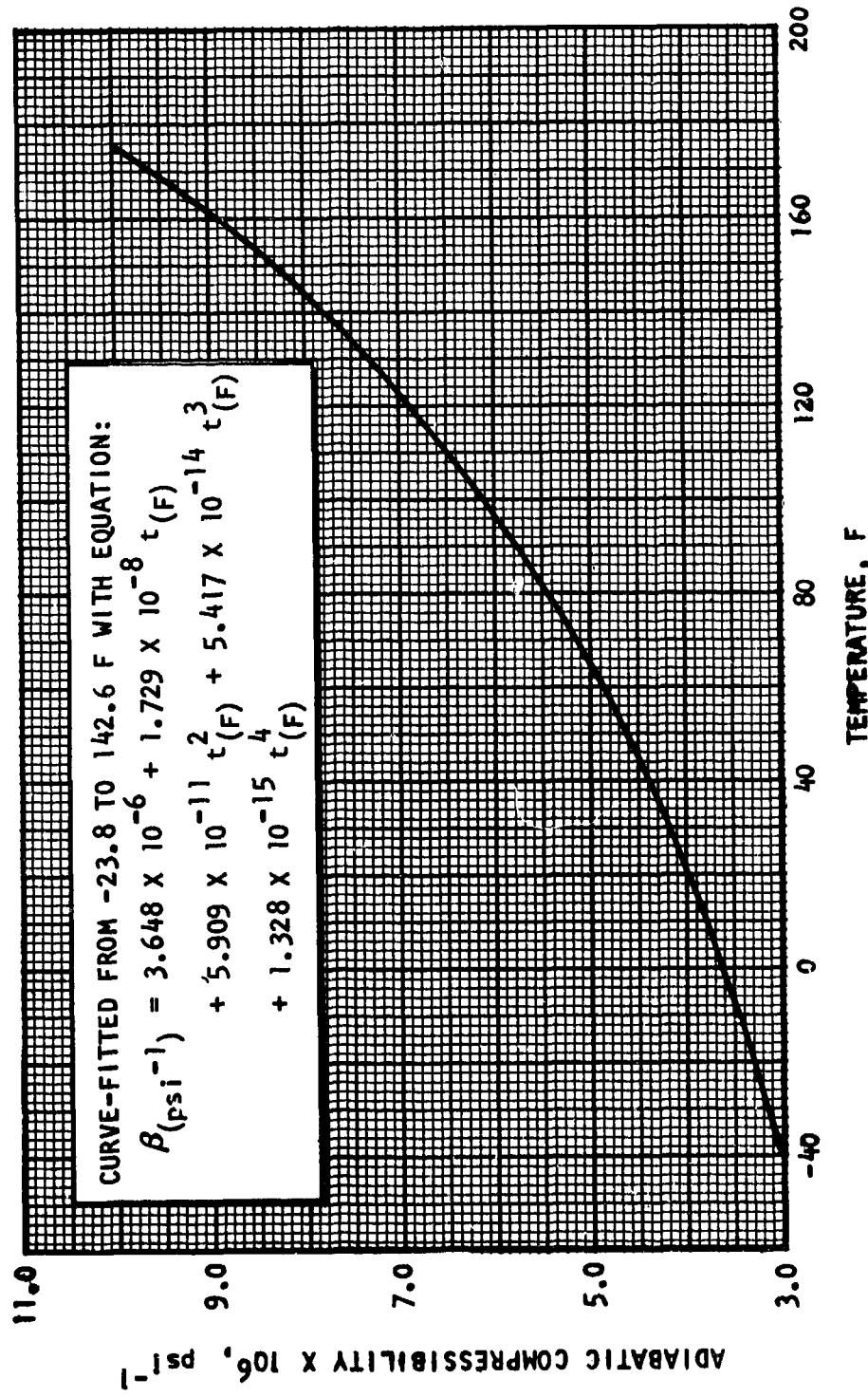


Figure E-2a. Adiabatic Compressibility of Fluorox (Ref. E-3)

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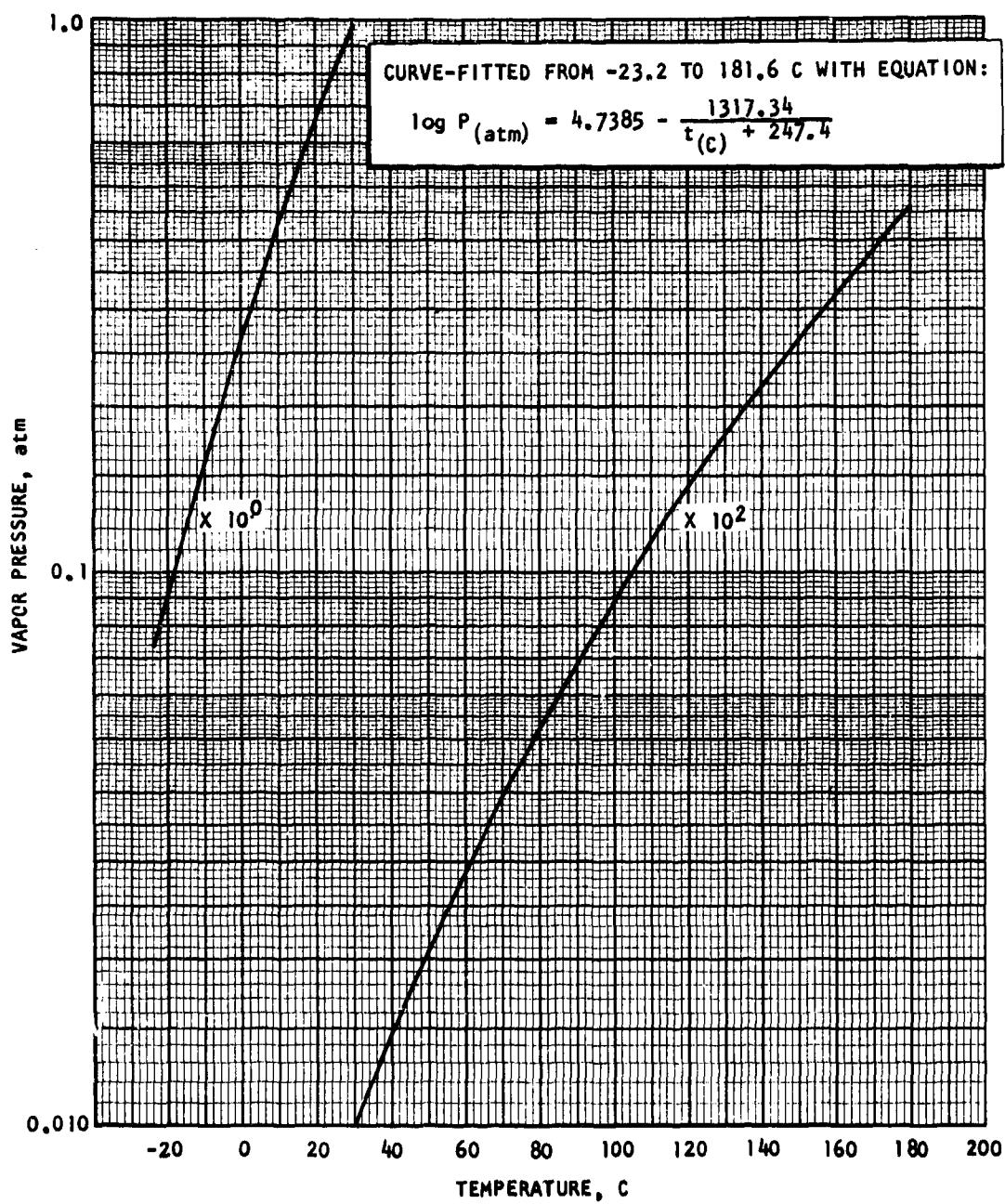


Figure E-3. Vapor Pressure of Florox (Ref. E-3)

E-11

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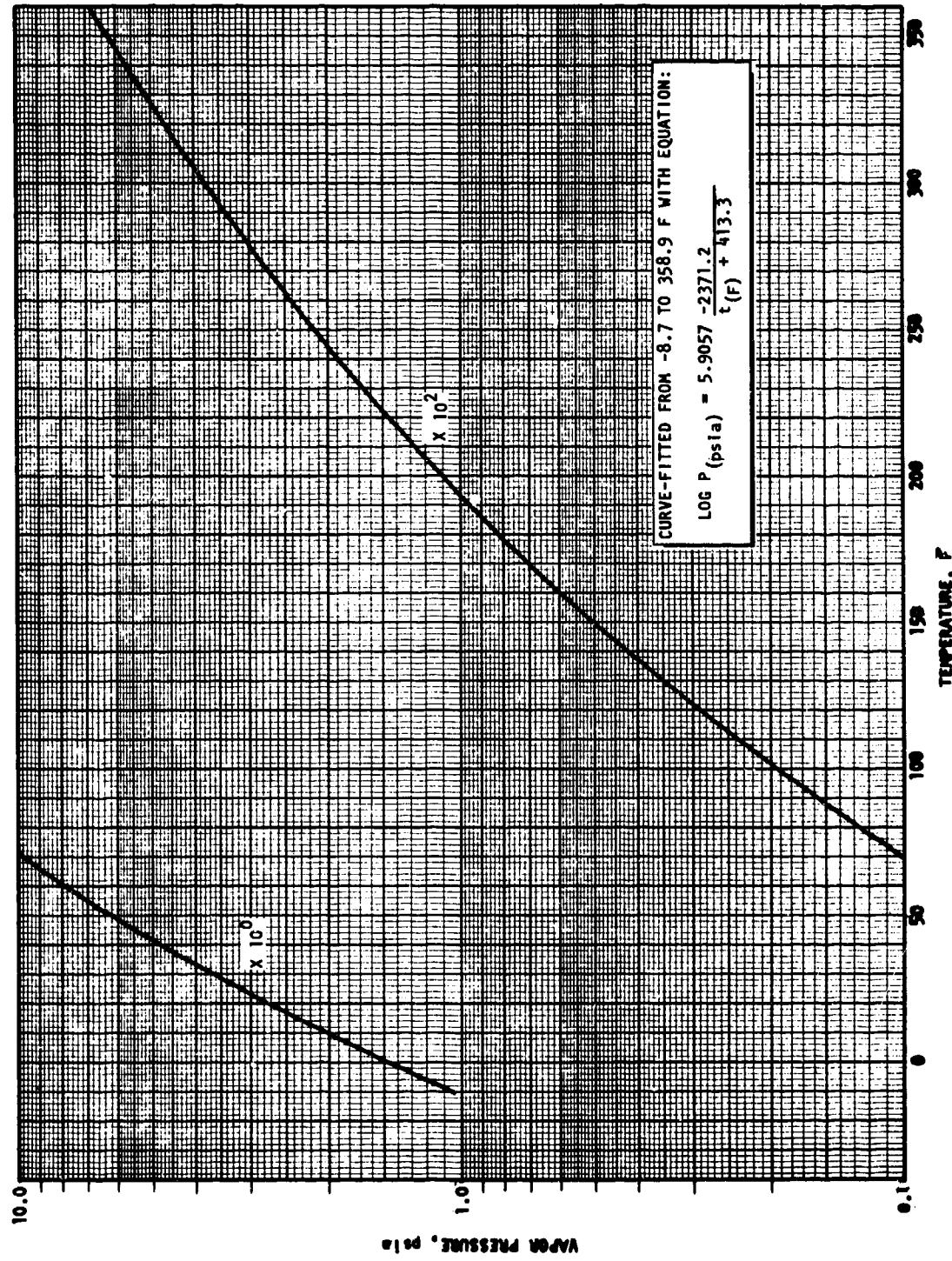


Figure 3a. Vapor Pressure of Fluorox (Ref. E-3)

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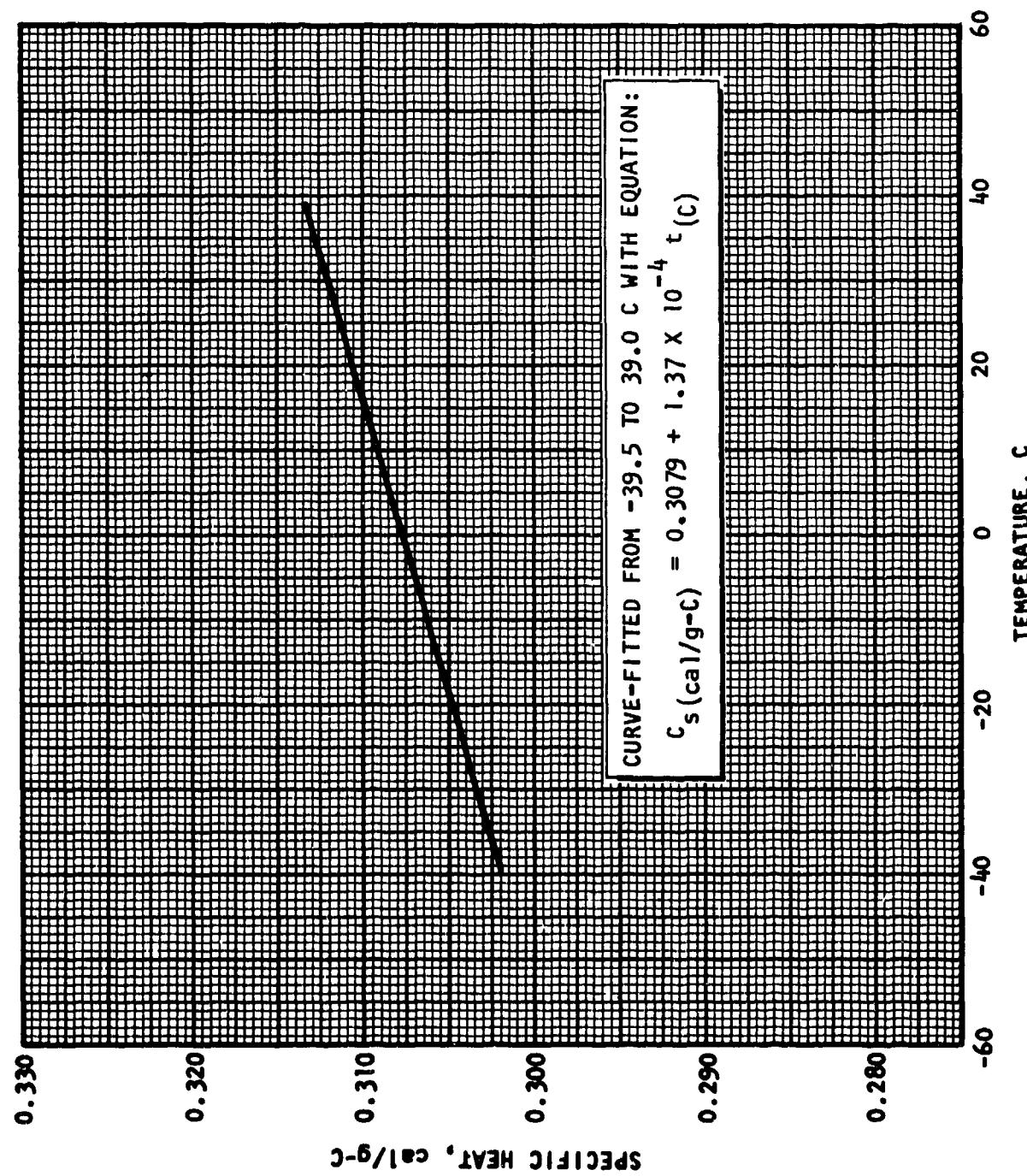


Figure E-4. Specific Heat of Saturated Liquid Florox (Ref. E-3)

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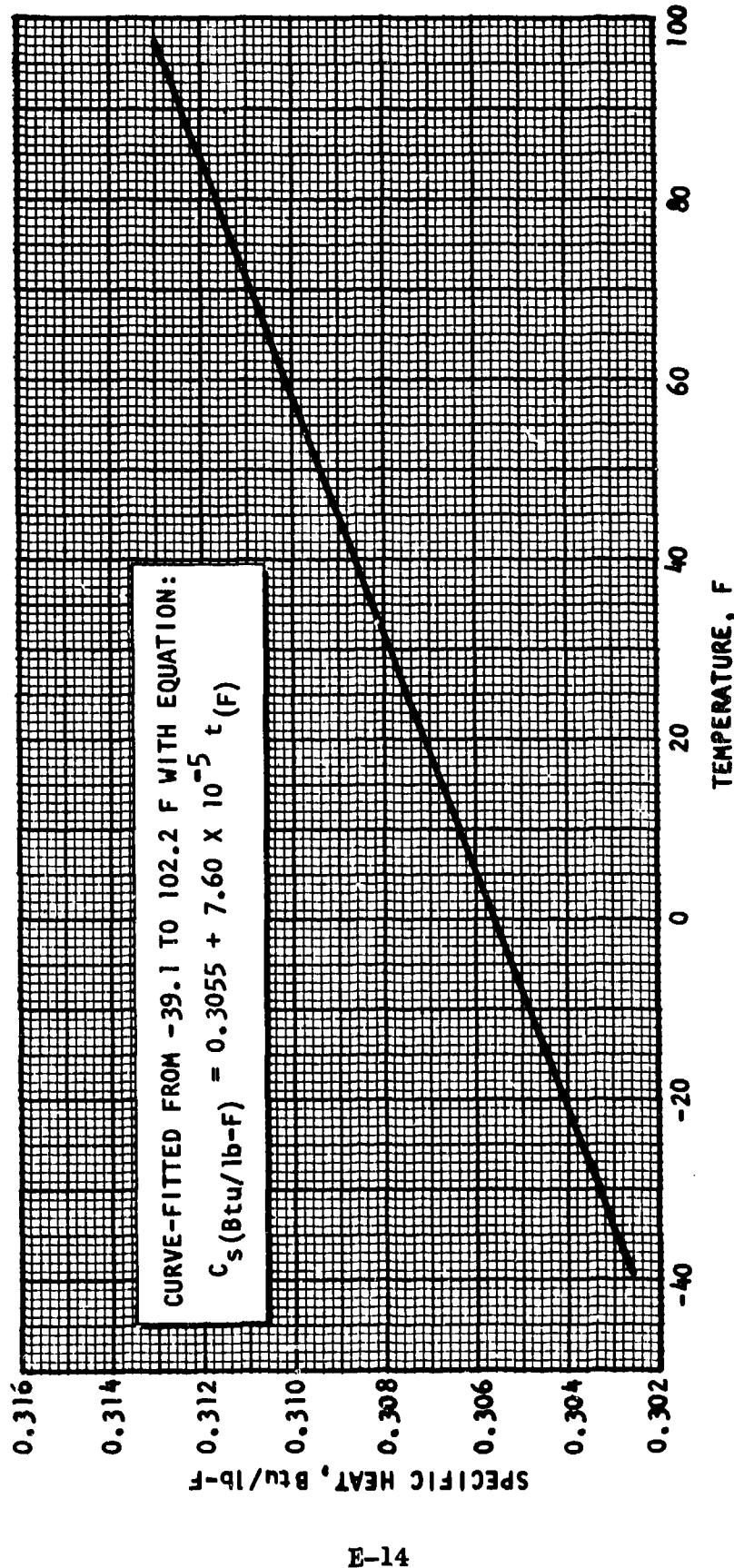


Figure E-4a. Specific Heat of Saturated Liquid Fluorox (Ref. E-3)

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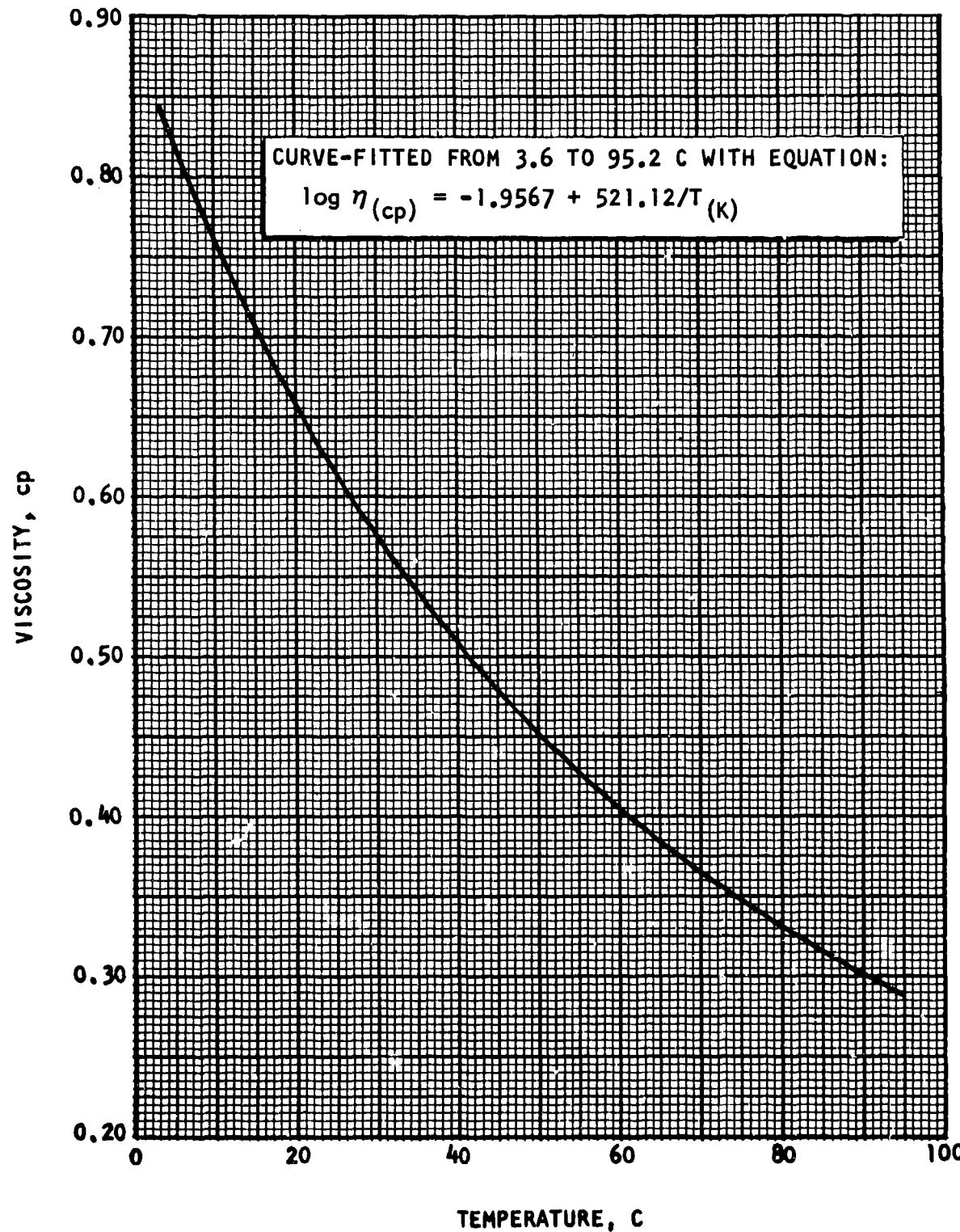


Figure E-5. Viscosity of Saturated Liquid Florox

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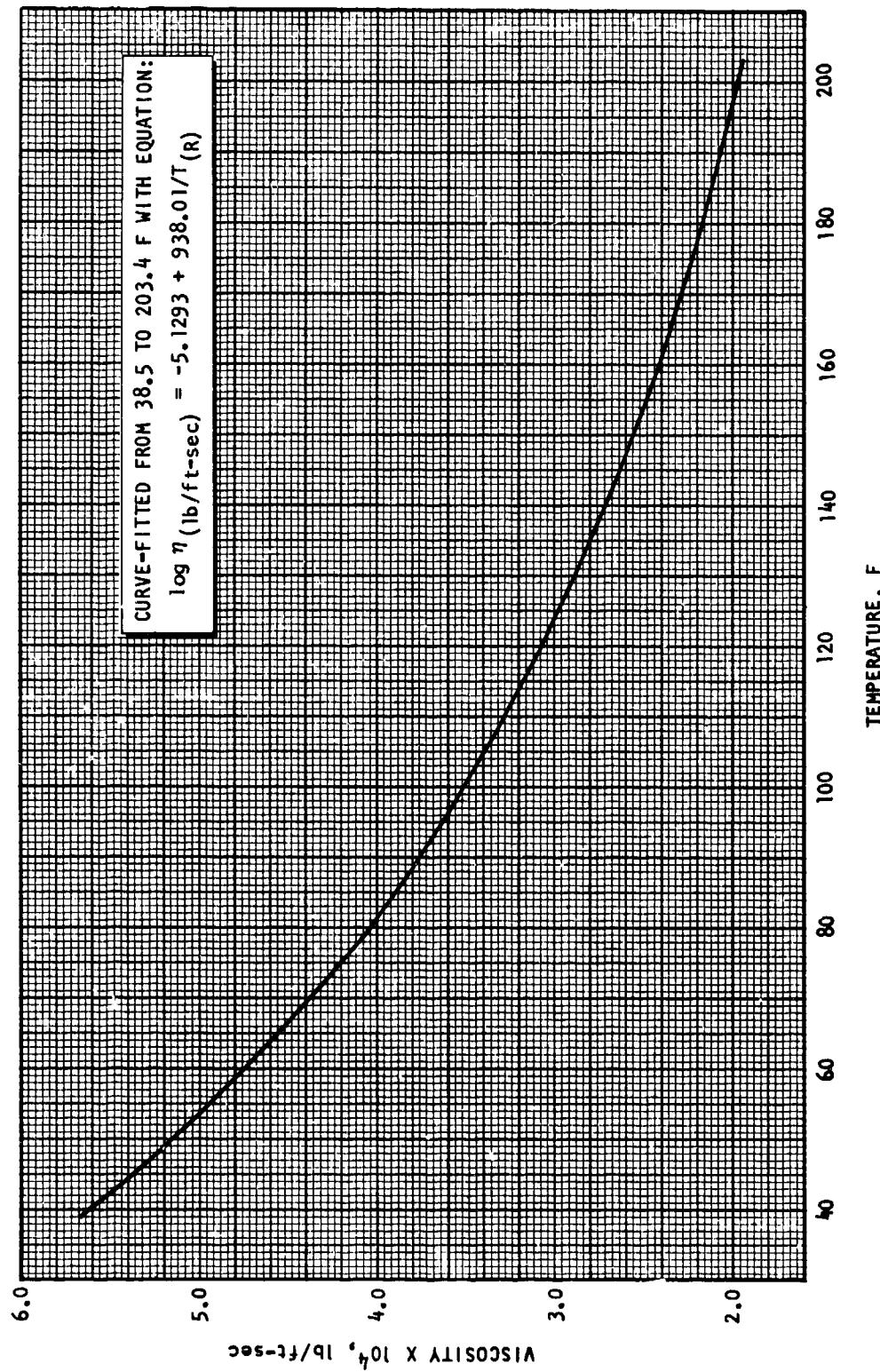


Figure E-5a. Viscosity of Saturated Liquid Fluorox (Ref. E-3)

E-16

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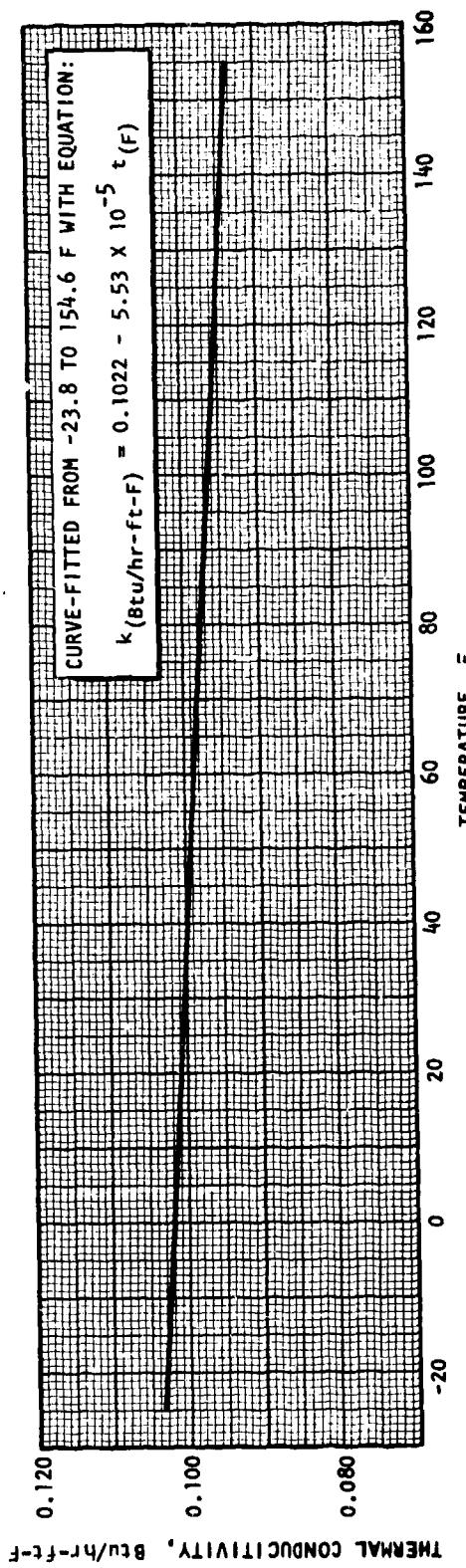
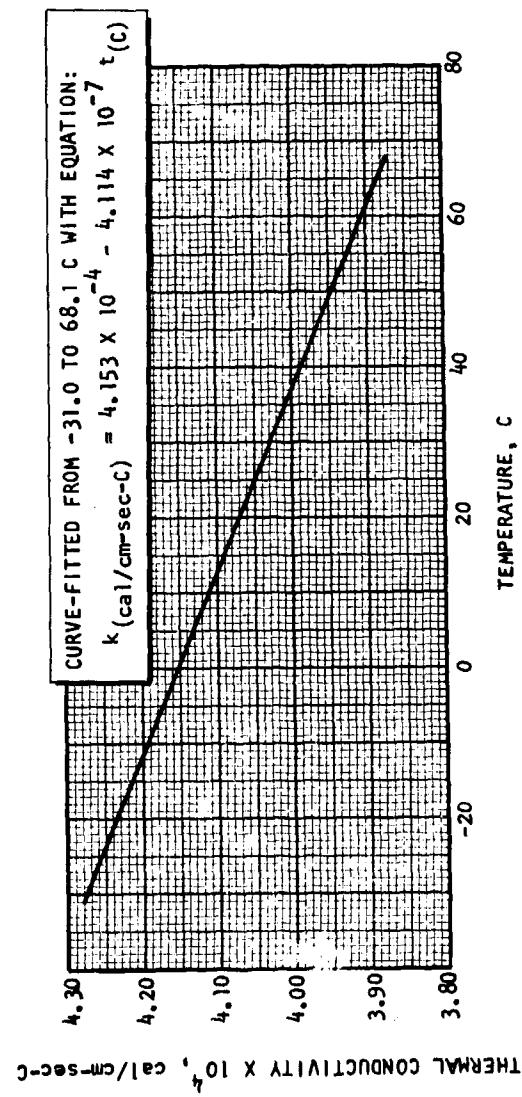


Figure E-6. Thermal Conductivity of Saturated Liquid Flurox (Ref. E-3)

E-17

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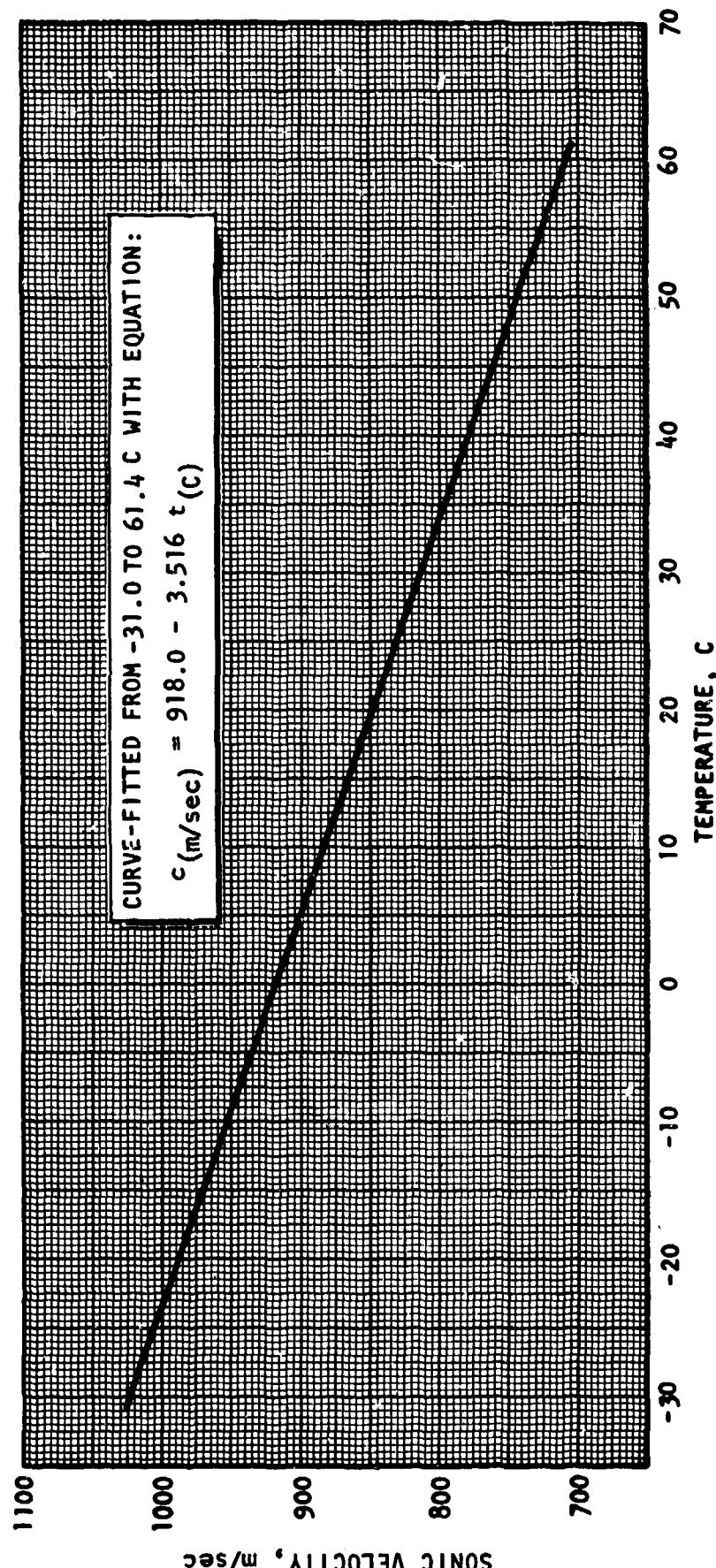


Figure E-7. Velocity of Sound in Saturated Liquid Fluorox (Ref. E-3)

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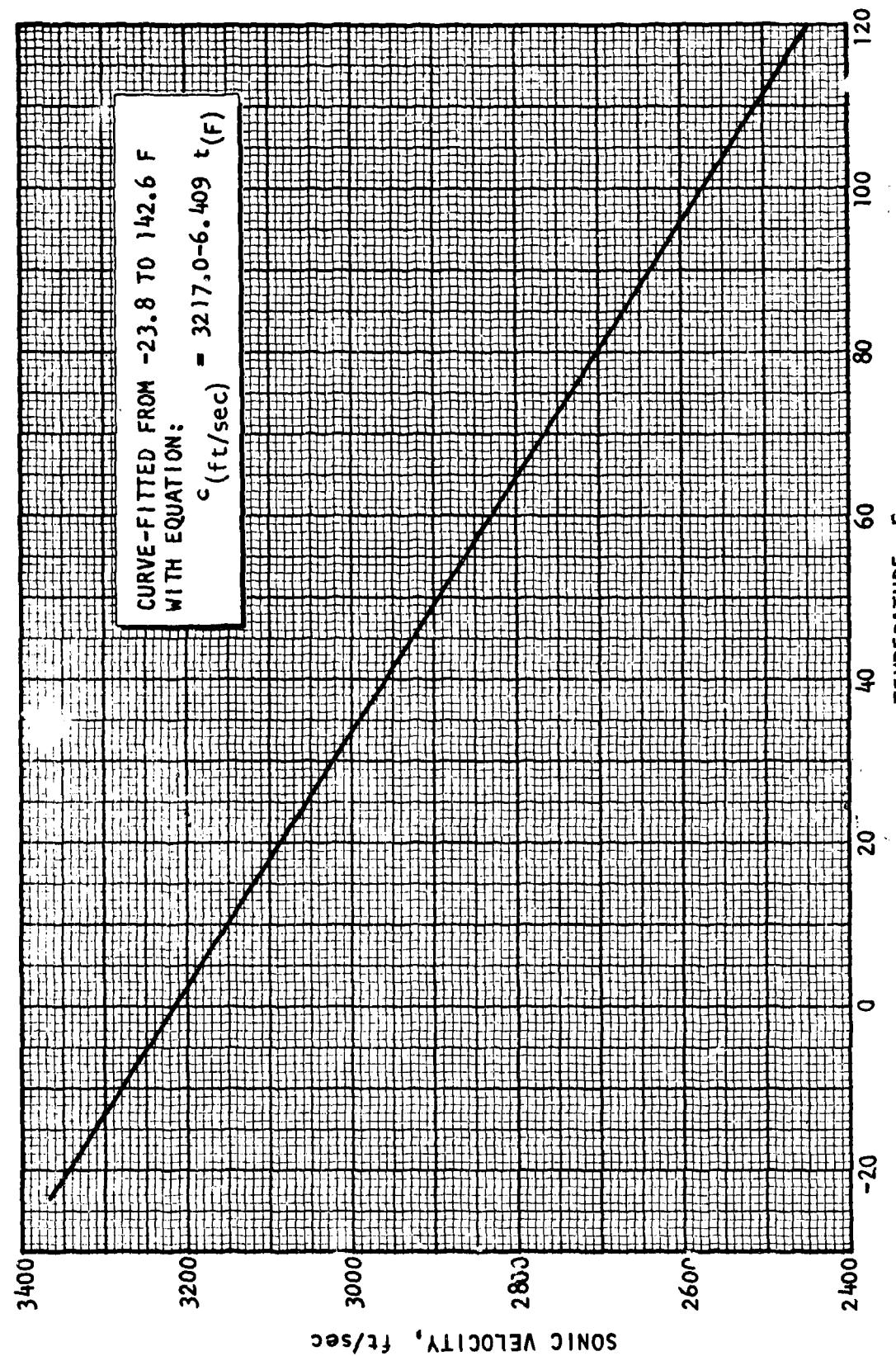


Figure E-7a. Velocity of Sound in Saturated Liquid Fluorox (Ref. E-3)

E-19/E-20

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APPENDIX F

PHYSICAL PROPERTIES OF MOR-5

(U) The physical and thermodynamic properties of MOR-5 are presented in Table F-1. Figures F-1 through F-6 are graphical illustrations of the properties listed in Table F-1.

F-1

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TABLE F-1

PHYSICAL PROPERTIES OF MOR-5 AT 25 C (77 F)

Property	Value		Figure Number	Reference Number
	Metric	English		
General Identification				
Identification	MOR-5			
Molecular Formula	78 w/o ClF_3 0 - 22 w/o ClF_5 (nominal)			
Effective Molecular Weight*	112.625 g/g-mole	112.625 lb/lb-mole		F-1
Melting Point	-46.2 C	-51.2 F	F-1,-1a	F-2
Triple Point	9.4 C	48.9 F		F-3
Normal Boiling Point				
Critical Properties				
Temperature				
Pressure				
Density				
Volume				
Phase Properties				
Density				
Solid				
Liquid	1.837 g/cc	114.67 lb/cu ft	F-2,-2a	
Gas				F-3

F-2

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*Calculation based on 100 grams of solution and corresponding to a molecular formula of $\text{Cl}_0.888\text{F}_3.0010.719$.

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TABLE F-1
PHYSICAL PROPERTIES OF MOR-5 AT 25 C (77 F)
(Continued)

Property	Value		Figure Number	Reference Number
	Metric	English		
Thermal Expansion (cubic)				
Compressibility				
Adiabatic				
Isothermal				
Vapor Pressure	1.743 atm	25.61 psia	F-3, -3a	F-2
Surface Tension				
Inert-Gas Solubility				
<u>Thermodynamic Properties</u>				
Heats of				
Formation (liquid)*	-43.57 Kcal/mole	-696.4 Btu/lb		
Fusion				
Vaporization**	5.969 Kcal/mole at NBP	95.40 Btu/lb at NBP		F-3
Heat Capacity				
Solid				
Liquid	0.303 cal/g-C	0.303 Btu/lb-F	F-4, -4a	F-3
Gas				

F-3

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*Calculation based on 100 grams of solution and a corresponding to a molecular formula of

$C1.0.888 F 3.001 0.719$.

**Calculated from vapor pressure equation.

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TABLE F-1

PHYSICAL PROPERTIES OF MOR-5 AT 25 C (77 F)
(Continued)

Property	Value		Figure Number	Reference Number
	Metric	English		
Entropy				
Enthalpy				
<u>Transport Properties</u>				
Viscosity	0.526 cp	3.533×10^{-4} lb/ft sec	F-5, -5a	F-3
Liquid				
Gas				
Thermal Conductivity	4.220×10^{-4} cal/cm-sec-C	0.1020 Btu/hr-ft-F	F-6	F-3
Liquid				
Gas				
Sonic Velocity				
Liquid				
Gas				
<u>Electromagnetic Properties</u>				
Index of Refraction				
Liquid				
Gas				
Dipole Moment				

F-4

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TABLE F-1

PHYSICAL PROPERTIES OF MOR-5 AT 25 C (77 F)
(concluded)

Property	Value Metric	Value English	Figure Number	Reference Number
Dielectric Constant				
Liquid				
Gas				
Electrical Conductivity				
Magnetic Susceptibility				

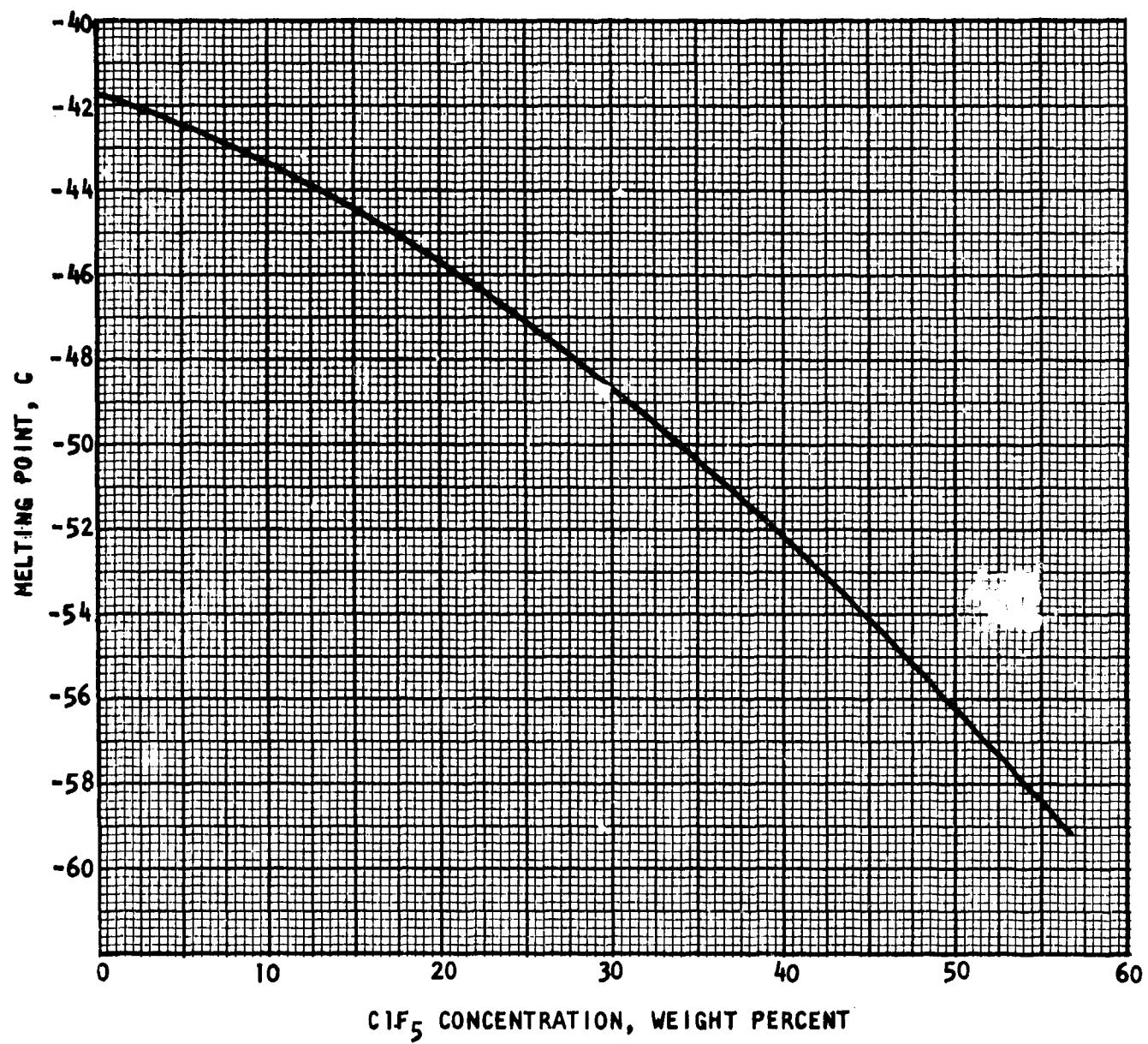
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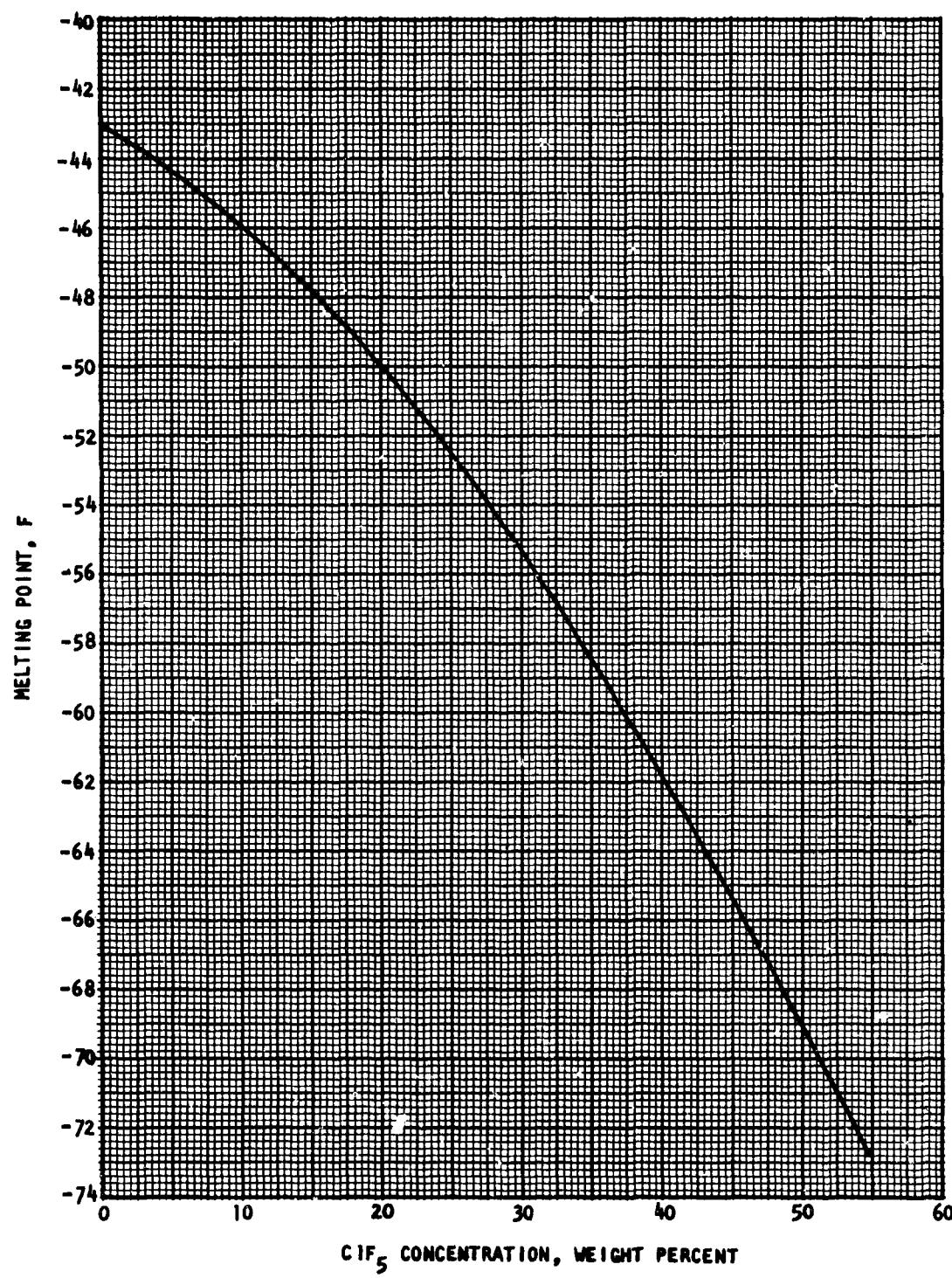


(C) Figure F-1. Melting Points of the ClF₃O - ClF₅ System (Ref. F-2)

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(C) Figure F-1a. Melting Points of the $\text{ClF}_3\text{O} - \text{ClF}_5$ System (Ref. F-2)

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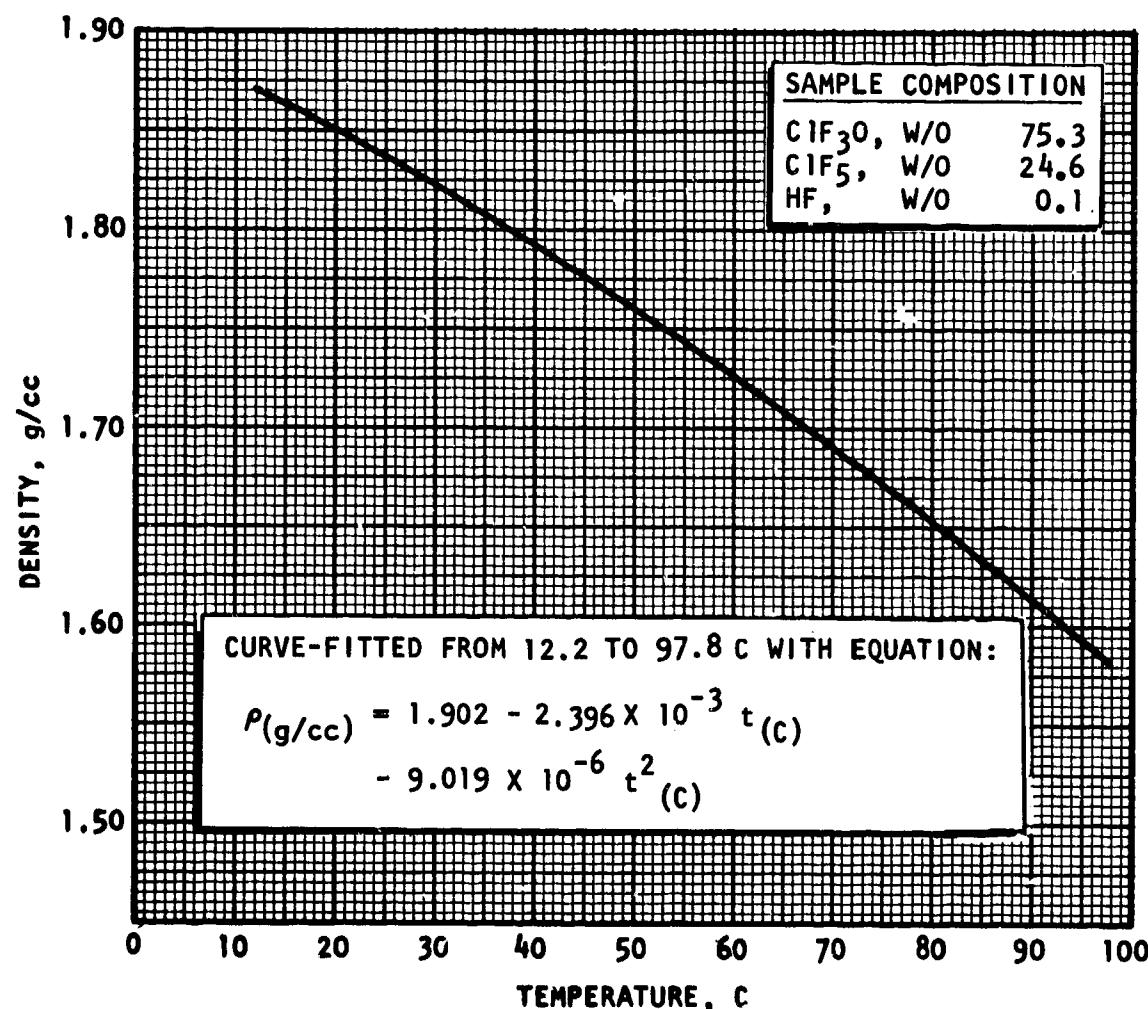


Figure F-2. Density of Saturated Liquid MOR-5 (Ref. F-3)

F-9

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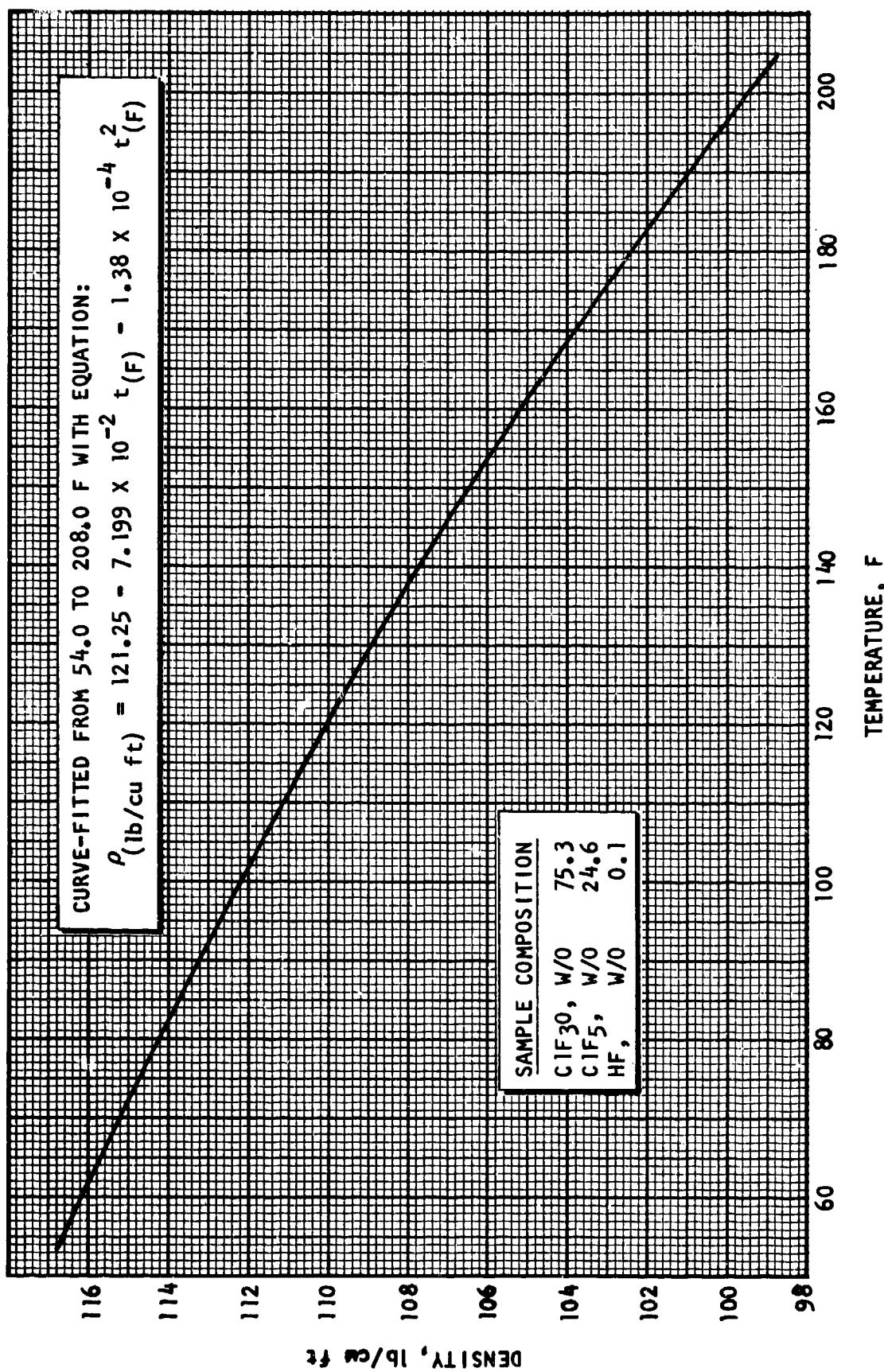


Figure F-2a. Density of Saturated Liquid MOR-5 (Ref. F-3)

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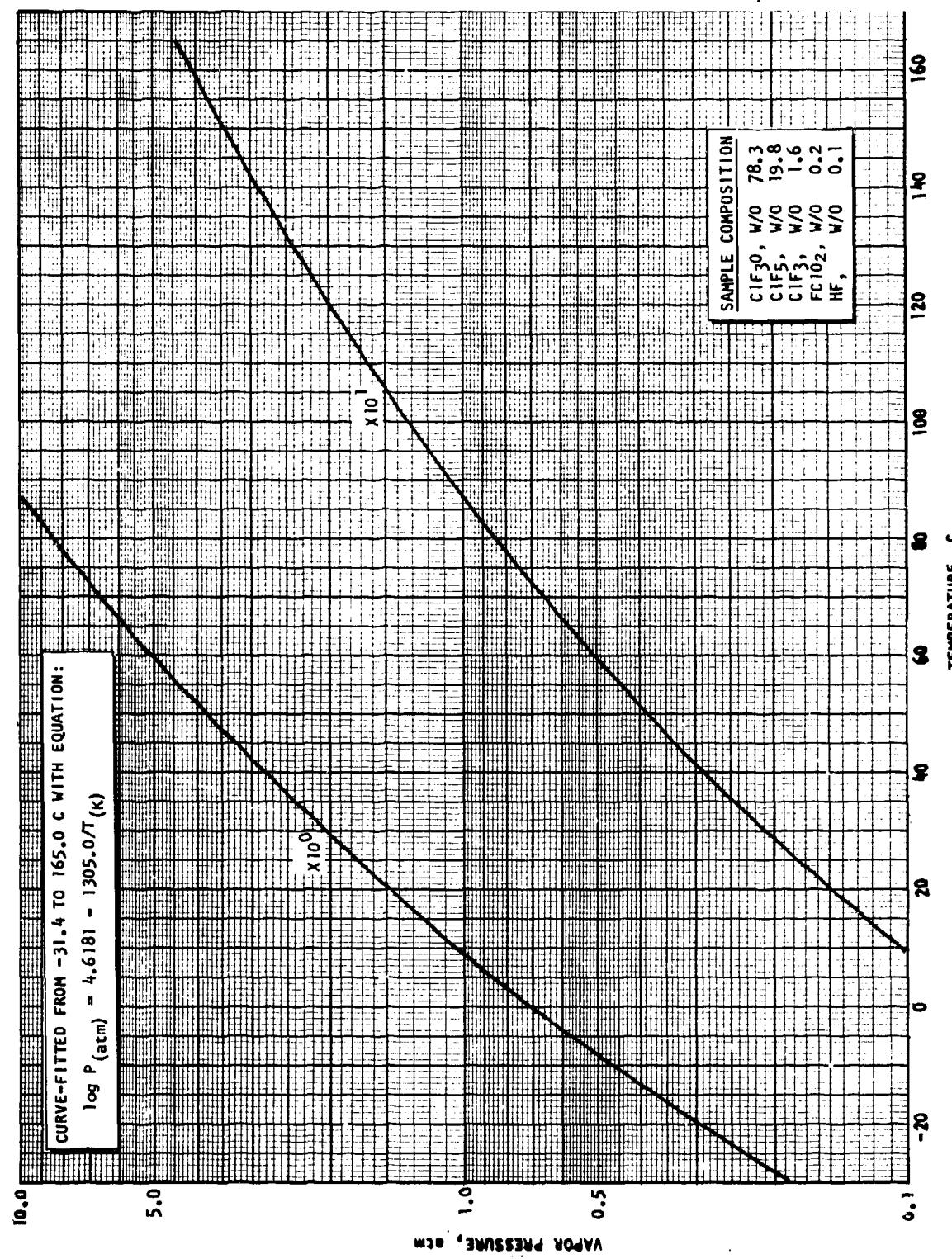


Figure F-3. Vapor Pressure of MOR-5 (Ref. F-3)

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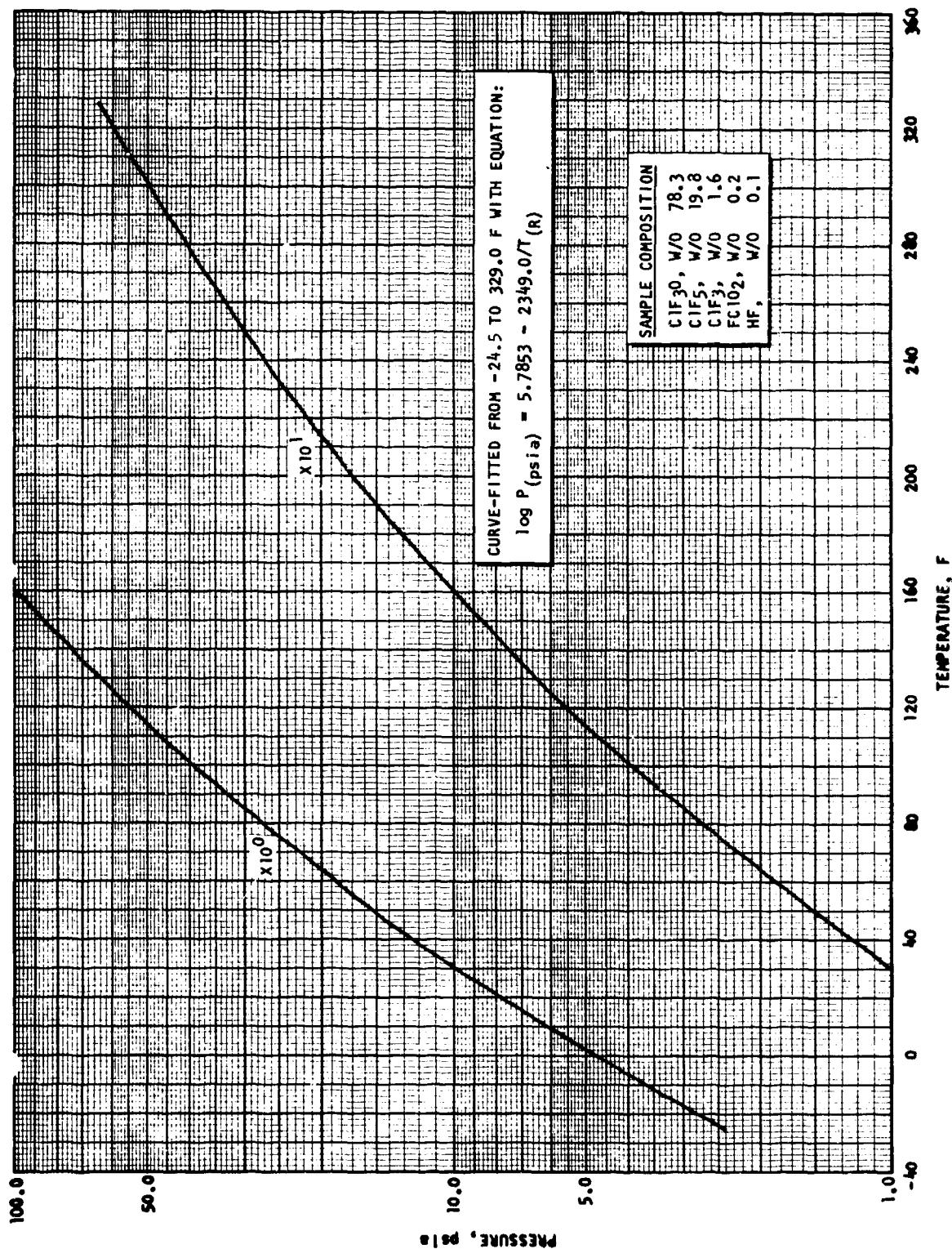


Figure F-3a. Vapor Pressure of MOR-5 (Ref. F-3)

F-12

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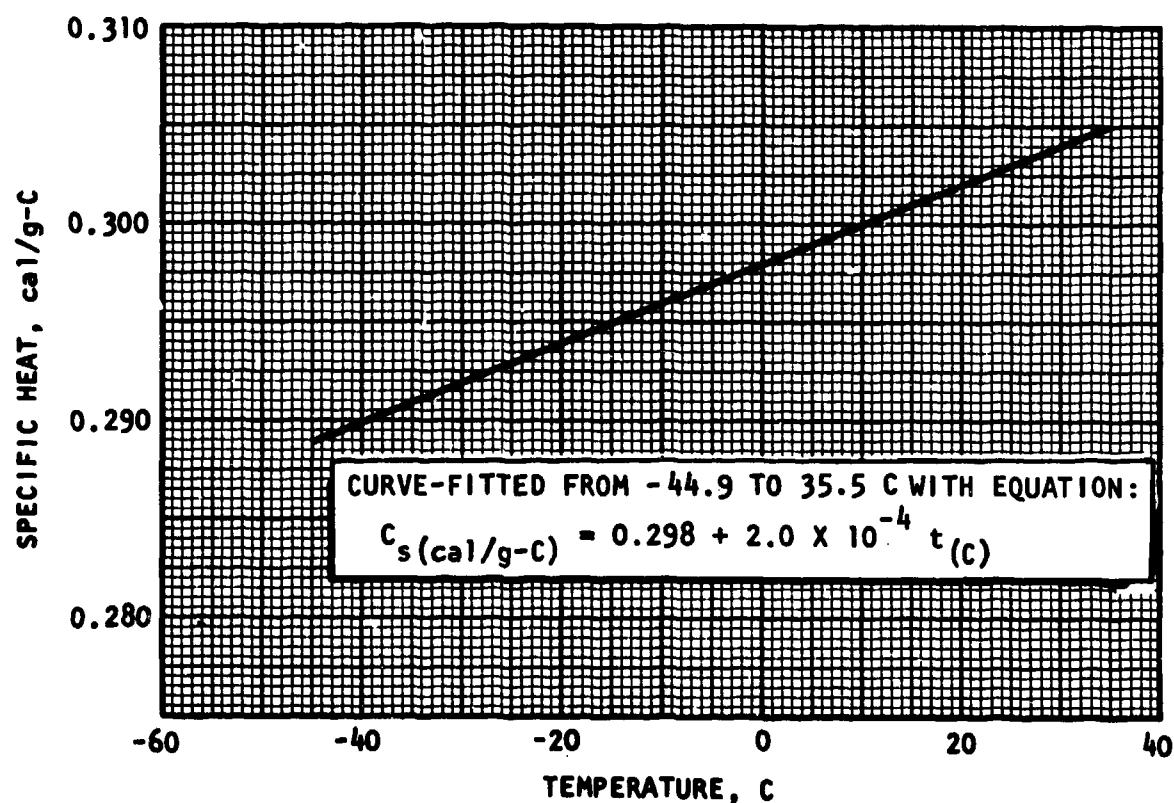


Figure F-4. Specific Heat of Saturated Liquid MOR-5 (Ref. F-3)

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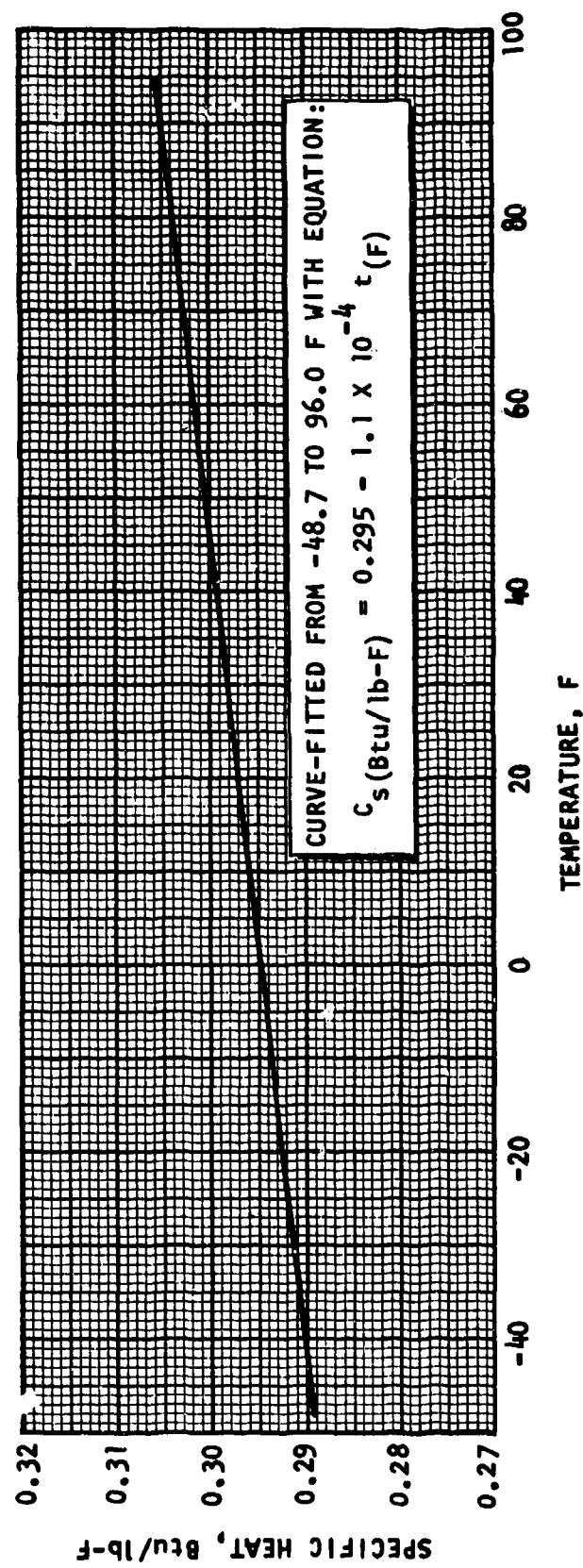


Figure F-4a. Specific Heat of Saturated Liquid MOR-5 (Ref. F-3)

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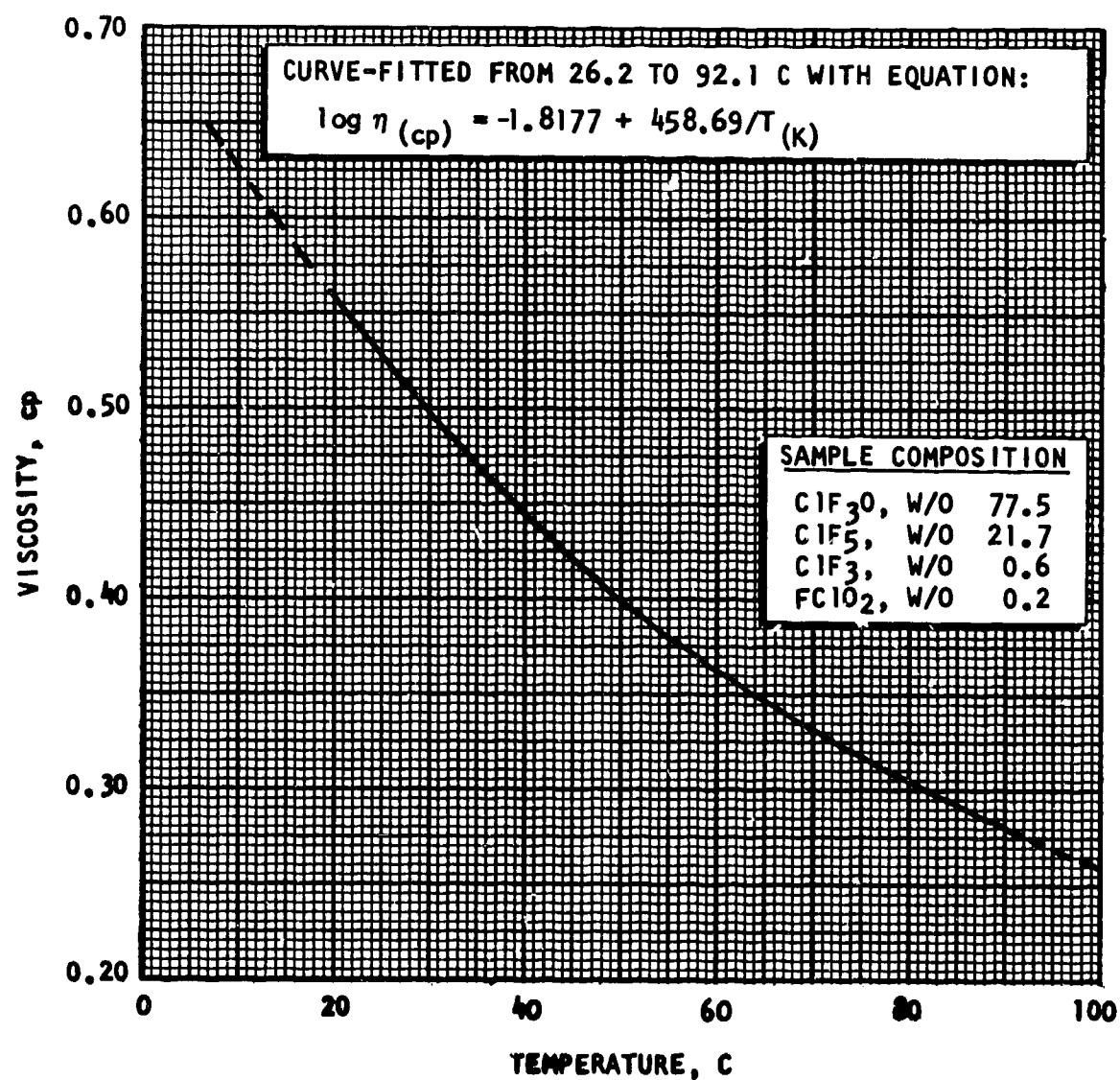


Figure F-5. Viscosity of Saturated Liquid MOR-5 (Ref. F-3)

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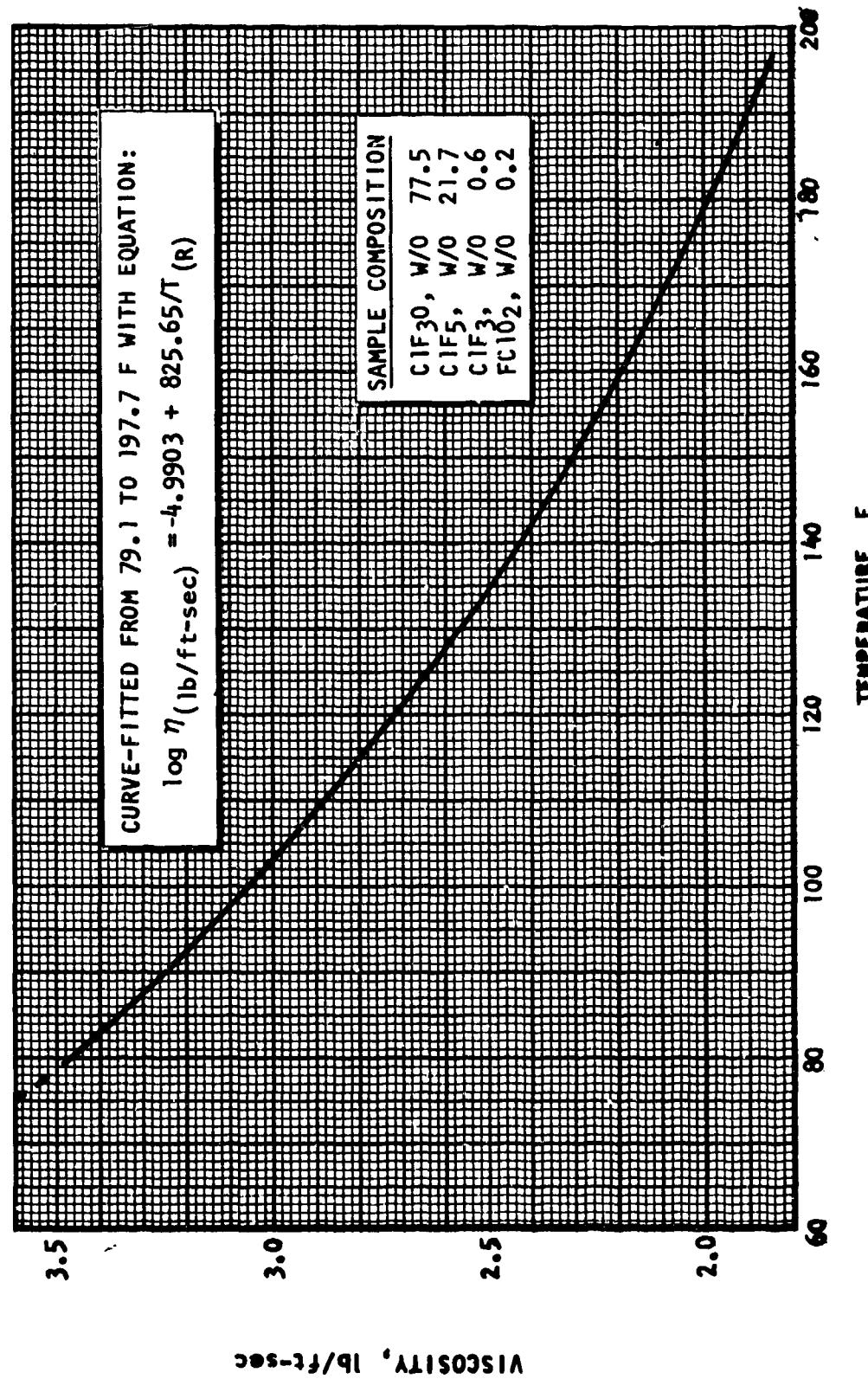


Figure F-5a. Viscosity of Saturated Liquid MOR-5 (Ref. F-3)

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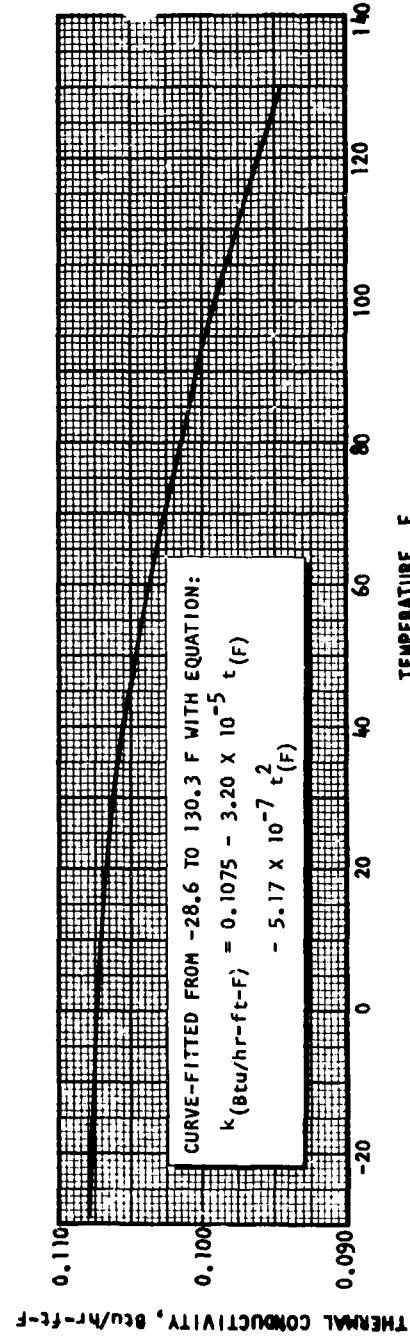
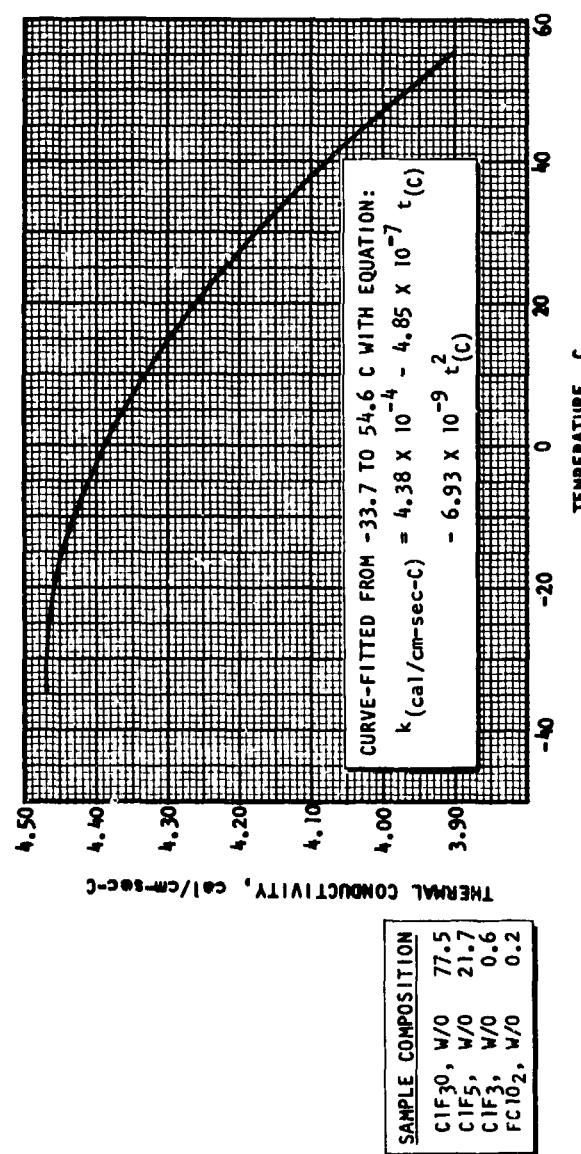


Figure F-6. Thermal Conductivity of Saturated Liquid MOR-5 (Ref. F-3)

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APPENDIX G

PHYSICAL PROPERTIES OF MHF-7

(U) The physical and thermodynamic properties of the nominal MHF-7 formulation are presented in Table G-1. Figures G-1 through G-7a are graphical illustrations of the properties listed in Table G-1 for the nominal formulation. Expressions of MHF-7 properties as functions of temperature and composition (over a \pm 5 w/o variation in each of the major ingredients) are presented in Table G-2.

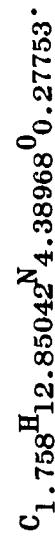
TABLE G-1

PHYSICAL PROPERTIES OF MHF-7 AT 25 C (77 F)

Property	Value		Figure Number	Reference Number
	Metric	English		
<u>General Identification</u>				
Identification	MHF-7			
Molecular Formula	81 w/o $\text{CH}_3\text{N}_2\text{H}_3\text{-}14$ w/o $\text{N}_2\text{H}_4\text{-}5$ w/o H_2O (nominal)			
Effective Molecular Weight*	40.447 g/g-mole	40.447 lb/lb-mole		G-1
Melting Point	-57.0 C	-70.6 F		G-2
Triple Point				
Normal Boiling Point	87.4 C	189.3 F		G-2
<u>Critical Properties</u>				
Temperature	332 C **	630 F **		
Pressure	168 atm **	1570 psia **		
Density	0.33 g/cc **	20.5 lb/cu ft **		
Volume	30 cc/g **	0.049 cu ft/lb **		
<u>Phase Properties</u>				
Density				
Solid				
Liquid	0.9023 g/cc	56.34 lb/cu ft	G-1,-1a	G-2
Gas				

G-2

*Calculation based on 166 grams of solution and corresponding to a molecular formula of



**Estimated pseudocritical constants for mixture.

TABLE G-1

PHYSICAL PROPERTIES OF MFH-7 AT 25 C (77 F)
(Continued)

Property	Value		Figure Number	Reference Number
	Metric	English		
Thermal Expansion (cubic)				
Compressibility	$4.182 \times 10^{-5} \text{ atm}^{-1}$	$2.846 \times 10^{-6} \text{ psi}^{-1}$	G-2,-2a	G-2
Adiabatic				
Isothermal	0.0829 atm	1.22 psia	G-3,-3a	G-2
Vapor Pressure				
Surface Tension				
Inert-Gas Solubility				
<u>Thermodynamic Properties</u>				
Heats of				
Formation (liquid)*	+3.480 Kcal/mole	+154.9 Btu/lb		
Fusion				
Vaporization**	8.944 Kcal/mole at NBP	398.02 Btu/lb at NBP		
Heat Capacity				
Solid	0.747 cal/g-C	0.747 Btu/lb-F	G-4,-4a	G-2
Liquid				
Gas				

G-3

*Calculation based on 100 grams of solution and corresponding to a molecular formula of

 $C_{1.758}H_{12.8504}N_{4.38968}O_{0.27753}$ with a heat of solution correction for the H_2O .

**Calculated from vapor pressure equation.

TABLE G-1

PHYSICAL PROPERTIES OF MHF-7 AT 25 C (77 F)
(Continued)

Property	Value		Figure Number	Reference Number
	Metric	English		
Entropy				
Enthalpy				
<u>Transport Properties</u>				
Viscosity				
Liquid	1.926 cp	6.892×10^{-4} lb/ft sec	G-5, -5a	G-2
Gas				
Thermal Conductivity				
Liquid	6.748×10^{-4} cal/cm-sec-C	0.1632 Btu/hr-ft-F	G-6, -6a	G-2
Gas				
Sonic Velocity				
Liquid	1639 m/sec	5379 ft/sec	G-7, -7a	G-2
Gas				
<u>Electromagnetic Properties</u>				
Index of Refraction				
Liquid				
Gas				
Dipole Moment				

TABLE G-1

PHYSICAL PROPERTIES OF MHF-7 AT 25 C (77 F)
(Concluded)

Property	Metric	Value	Figure Number	Reference Number
		English		
Dielectric Constant				
Liquid				
Gas				
Electrical Conductivity				
Magnetic Susceptibility				

TABLE G-2

PHYSICAL PROPERTIES OF LIQUID MHF-7 AS A FUNCTION OF
TEMPERATURE AND COMPOSITION (Ref. G-2)

Property	Temperature Range	Equation
Normal Boiling Point		$NBP(C) = \frac{496.6 + 5.757 H(w/o) + 7.919 W(w/o)}{7.3742 - 1.507 \times 10^{-2} H(w/o) - 2.073 \times 10^{-2} W(w/o)}$ $NBP(F) = \frac{1129.8 + 9.88 H(w/o) + 13.59 W(w/o)}{7.3742 - 1.507 \times 10^{-2} H(w/o) - 2.073 \times 10^{-2} W(w/o)}$
Density	-56.7 to 93.7 C	$\rho(g/cc) = 0.8956 - 9.779 \times 10^{-4} t(C) - 1.83 \times 10^{-7} t(C)^2$ $+ 2.652 \times 10^{-3} W(w/o) + 1.202 \times 10^{-3} H(w/o) + 5.11$ $\times 10^{-6} W(w/o) t(C) + 1.64 \times 10^{-6} H(w/o) t(C)$ $\rho(1b/cu ft) = 57.00 - 3.369 \times 10^{-2} t(F) - 3.53 \times 10^{-6} t(F)^2$ $+ 0.1599 W(w/o) + 7.325 \times 10^{-2} H(w/o) + 1.77$ $\times 10^{-4} W(w/o) t(F) + 5.67 \times 10^{-5} H(w/o) t(F)$
	-70.1 to 200.6 F	

TABLE G-2

PHYSICAL PROPERTIES OF LIQUID MFH-7 AS A FUNCTION OF
TEMPERATURE AND COMPOSITION (Ref. G-2)
(Continued)

Property	Temperature Range	Equation
Adiabatic Compressibility	-35.7 to 95.1 C	$\beta_s(\text{atm}^{-1}) = 4.2580 \times 10^{-5} + 2.7726 \times 10^{-7} t_{(C)} + 7.421 \times 10^{-10} t_{(C)}^2$ $- 3.735 \times 10^{-12} t_{(C)}^3 + 9.236 \times 10^{-14} t_{(C)}^4$ $- 3.040 \times 10^{-7} H_{(w/o)} - 4.056 \times 10^{-7} W_{(w/o)}$ $- 3.255 \times 10^{-9} H_{(w/o)} t_{(C)} - 5.684 \times 10^{-9} W_{(w/o)} t_{(C)}$
	-32.3 to 203.2 F	$\beta_s(\text{psi}^{-1}) = 2.5800 \times 10^{-6} + 9.2716 \times 10^{-9} t_{(F)} + 2.345 \times 10^{-11} t_{(F)}^2$ $- 1.202 \times 10^{-13} t_{(F)}^3 + 5.986 \times 10^{-16} t_{(F)}^4$ $- 1.675 \times 10^{-8} H_{(w/o)} - 2.072 \times 10^{-8} W_{(w/o)}$ $- 1.230 \times 10^{-10} H_{(w/o)} t_{(F)} - 2.149 \times 10^{-10} W_{(w/o)} t_{(F)}$
Vapor Pressure	-7.8 to 115.5 C	$\log P_{(\text{atm})} = 7.3742 - \frac{3313.5}{t_{(C)} + 382} - 1.507 \times 10^{-2} H_{(w/o)}$ $- 2.073 \times 10^{-2} W_{(w/o)}$

TABLE G-2

PHYSICAL PROPERTIES OF LIQUID MHF-7 AS A FUNCTION OF
TEMPERATURE AND COMPOSITION (Ref. G-2)
(continued)

Property	Temperature Range	Equation
Vapor Pressure (Cont.)	18.0 to 239.9 F	$\log P(\text{psia}) = 8.5414 - \frac{5964.3}{t(\text{F}) + 655.6} - 1.507 \times 10^{-2} H_{(w/o)}$ $- 2.073 \times 10^{-2} W_{(w/o)}$
Specific Heat	-52.35 to 68.69 C	$C_p \text{ (cal/g-C)} = 0.3335 + 2.635 \times 10^{-2} H_{(w/o)} + 8.469 \times 10^{-2} W_{(w/o)}$ $- 5.613 \times 10^{-3} H_{(w/o)} W_{(w/o)} + 5.87 \times 10^{-4} t_{(C)}$ $- 1.56 \times 10^{-5} H_{(w/o)} t_{(C)} + 3.12 \times 10^{-5} W_{(w/o)} t_{(w/o)}$ $+ 1.91 \times 10^{-6} t_{(C)}^2$
	-62.23 to 155.64 F	$C_p \text{ (Btu/lb-F)} = 0.3237 + 2.662 \times 10^{-2} H_{(w/o)} + 8.414 \times 10^{-2} W_{(w/o)}$ $- 5.613 \times 10^{-3} H_{(w/o)} W_{(w/o)} + 2.881 \times 10^{-4} t_{(F)}$ $- 8.64 \times 10^{-6} H_{(w/o)} t_{(F)} + 1.73 \times 10^{-5} W_{(w/o)} t_{(F)}$ $+ 5.89 \times 10^{-7} t_{(F)}^2$

TABLE G-2

PHYSICAL PROPERTIES OF LIQUID MHF-7 AS A FUNCTION OF
TEMPERATURE AND COMPOSITION (Ref. G-2)
(Continued)

Property	Temperature Range	Equation
Viscosity	-57.1 to 94.4 C	$\log \eta_{(c_p)} = -4.9085 + \frac{3614.4}{T(K)} - \frac{1.07370 \times 10^6}{T(K)^2} + \frac{1.26262 \times 10^8}{T(K)^3}$ $+ 0.10612 W_{(w/o)} - 3.540 \times 10^{-2} H_{(w/o)} - 76.579 W_{(w/o)}$
	-70.8 to 202.0 F	$+ \frac{22.601 H_{(w/o)}}{T(K)} + \frac{15264.6 W_{(w/o)}}{T(K)^2} - \frac{3551.7 H_{(w/o)}}{T(K)^2}$ $\log \eta_{(lb/ft sec)} = -8.0809 + \frac{6505.63}{T(R)} - \frac{3.47864 \times 10^6}{T(R)^2}$ $+ \frac{7.36338 \times 10^8}{T(R)^3} + 0.10612 W_{(w/o)}$ $- 3.540 \times 10^{-2} H_{(w/o)} - \frac{137.843 W_{(w/o)}}{T(R)}$ $+ \frac{40.683 H_{(w/o)}}{T(R)} + \frac{49457.5 W_{(w/o)}}{T(R)^2} - \frac{11507.8 H_{(w/o)}}{T(R)^2}$

TABLE G-2

PHYSICAL PROPERTIES OF LIQUID MHF-7 AS A FUNCTION OF
TEMPERATURE AND COMPOSITION (Ref. G-2)
(Continued)

Property	Temperature Range	Equation
Thermal Conductivity	-27.1 to 72.3 C	$K(\text{cal/cm-sec-C}) = 4.142 \times 10^{-4} + 1.138 \times 10^{-5} t(\text{C})$ $1.46 \times 10^{-7} t(\text{C})^2 + 1.273 \times 10^{-5} H(w/o)$ $- 2.48 \times 10^{-6} W(w/o) - 3.55 \times 10^{-7} H(w/o) t(\text{C})$ $- 9.5 \times 10^{-8} W(w/o) t(\text{C}) + 2.8 \times 10^{-9} H(w/o) t(\text{C})^2$ $+ 4.2 \times 10^{-9} W(w/o) t(\text{C})^2$
	-16.8 to 162.2 F	$K(\text{Btu/hr-ft-F}) = 4.005 \times 10^{-2} + 2.229 \times 10^{-3} t(\text{F})$ $- 1.09 \times 10^{-5} t(\text{F})^2 + 4.82 \times 10^{-3} H(w/o)$ $+ 1.30 \times 10^{-4} W(w/o) - 6.11 \times 10^{-5} H(w/o) t(\text{F})$ $- 3.28 \times 10^{-5} W(w/o) t(\text{F}) + 2.1 \times 10^{-7} H(w/o) t(\text{F})^2$ $+ 3.1 \times 10^{-7} W(w/o) t(\text{F})^2$

TABLE G-2

PHYSICAL PROPERTIES OF LIQUID MF-7 AS A FUNCTION OF
TEMPERATURE AND COMPOSITION (Ref. G-2)
(concluded)

Property	Temperature Range	Equation
Sonic Velocity	-35.7 to 95.1 C	$c \text{ (m/sec)} = 1618.5 - 4.003t \text{ (C)} + 5.96 H_{(w/o)} + 7.56 W_{(w/o)}$
	-32.3 to 203.2 F	$c \text{ (ft/sec)} = 5543.4 - 7.296t \text{ (F)} + 19.55 H_{(w/o)} + 24.80 W_{(w/o)}$

NOMENCLATURE

$t \text{ ()}$ - temperature in degrees (C) or (F)
 $T \text{ ()}$ - temperature in degrees (K) or (R)
 $H_{(w/o)}$ - N_2H_4 concentration in weight percent (w/o)
 $W_{(w/o)}$ - H_2O concentration in weight percent (w/o)
 $NBP \text{ ()}$ - normal boiling point in degrees (C) or (F)
 $\rho \text{ ()}$ - density in (g/cc) or (lb/cu ft)
 $\beta_s \text{ ()}$ - adiabatic compressibility in (atm^{-1}) or (psi^{-1})
 $P \text{ ()}$ - vapor pressure in (atm) or (psia)
 $C_p \text{ ()}$ - specific heat in (cal/g-C) or (Btu/lb-F)
 $\eta \text{ ()}$ - viscosity in (cp) or (lb/ft sec)
 $K \text{ ()}$ - thermal conductivity in (cal/cm-sec-C) or (Btu/hr-ft-F)
 $c \text{ ()}$ - sonic velocity in (m/sec) or (ft/sec)

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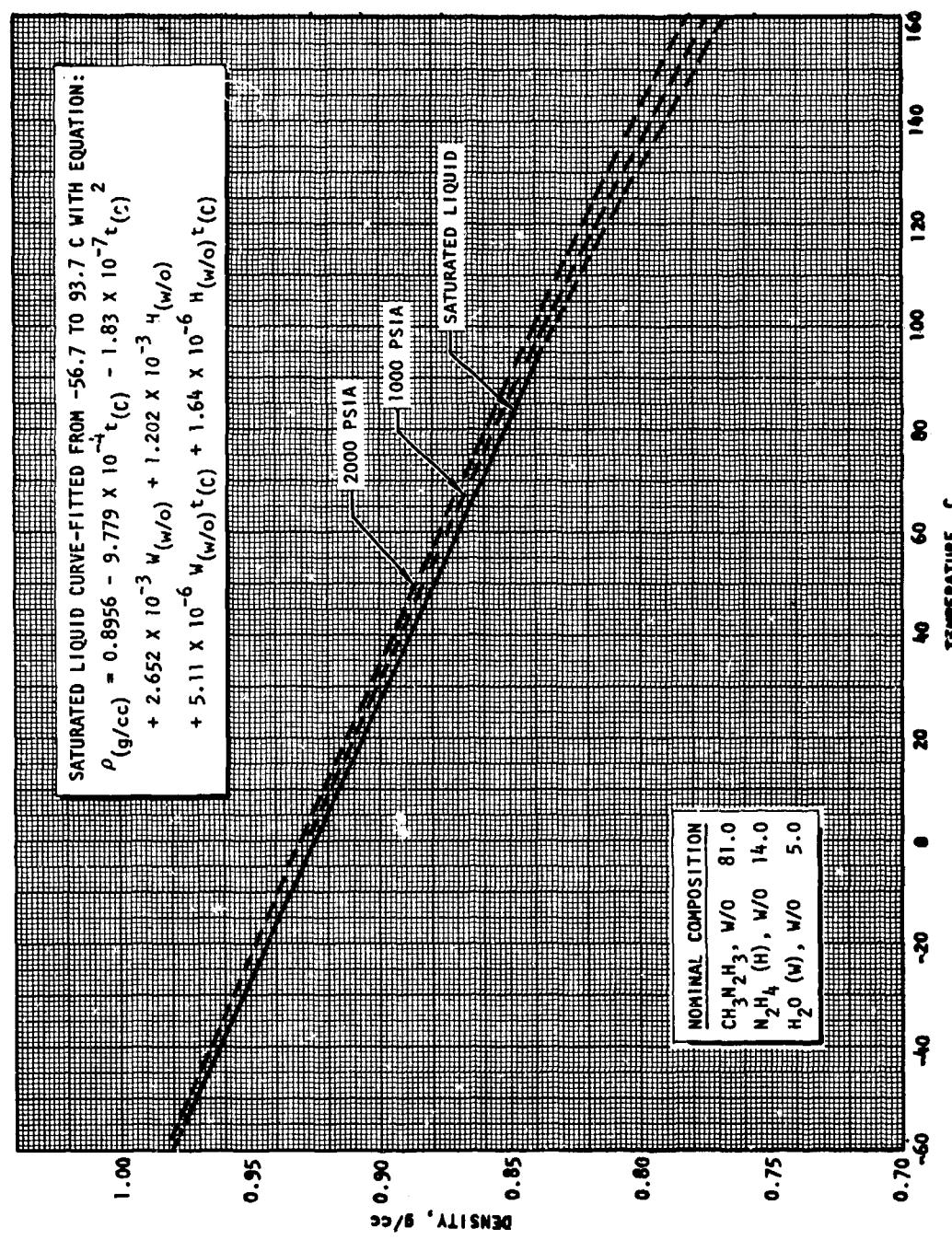


Figure G-1. Density of Liquid MF-7 (Ref. G-2)

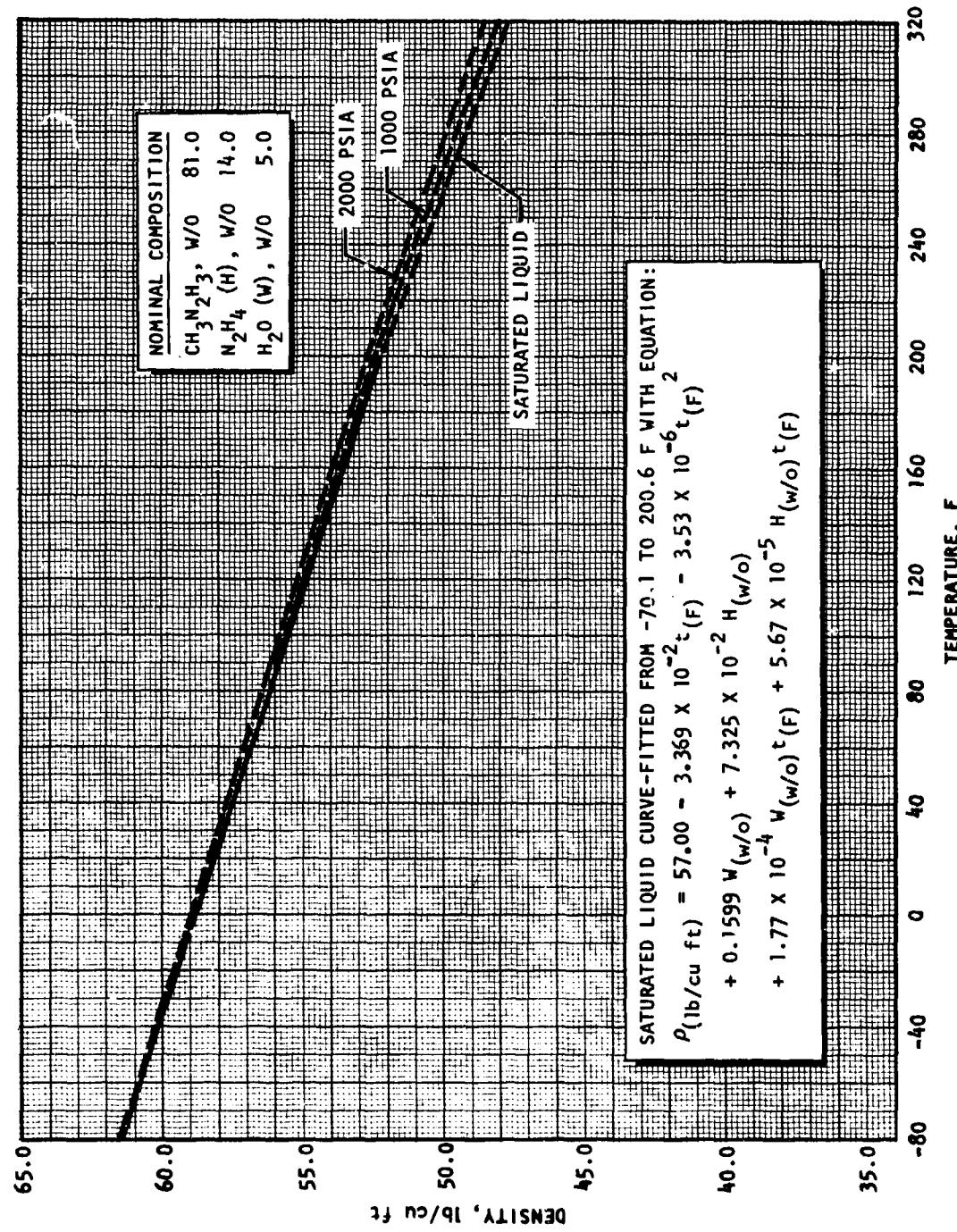


Figure G-1a. Density of Liquid MMF-7 (Ref. G-2)

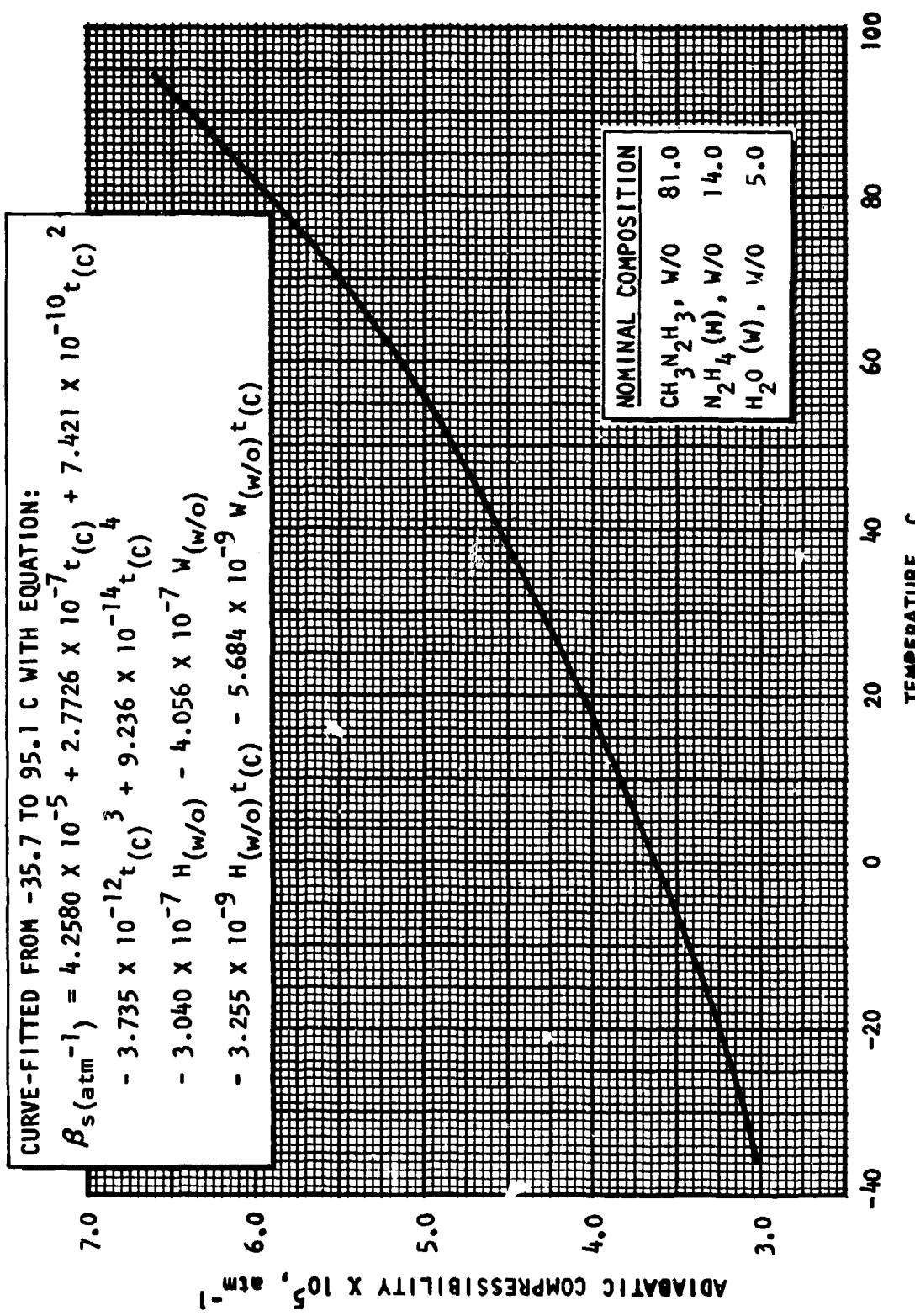


Figure G-2. Adiabatic Compressibility of Liquid MHF-7 (Ref. G-2)

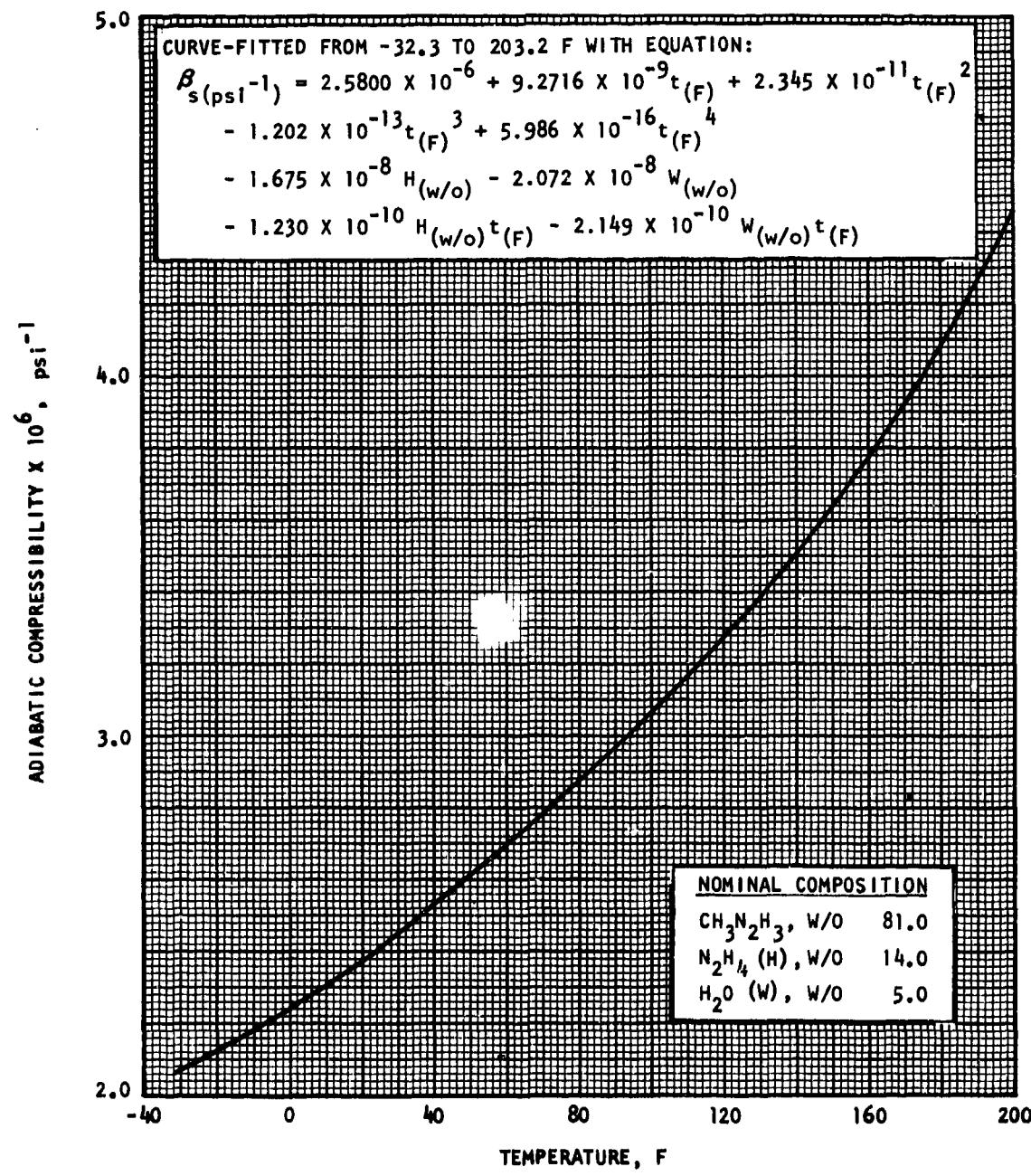


Figure G-2a. Adiabatic Compressibility of Liquid MHF-7 (Ref. G-2)

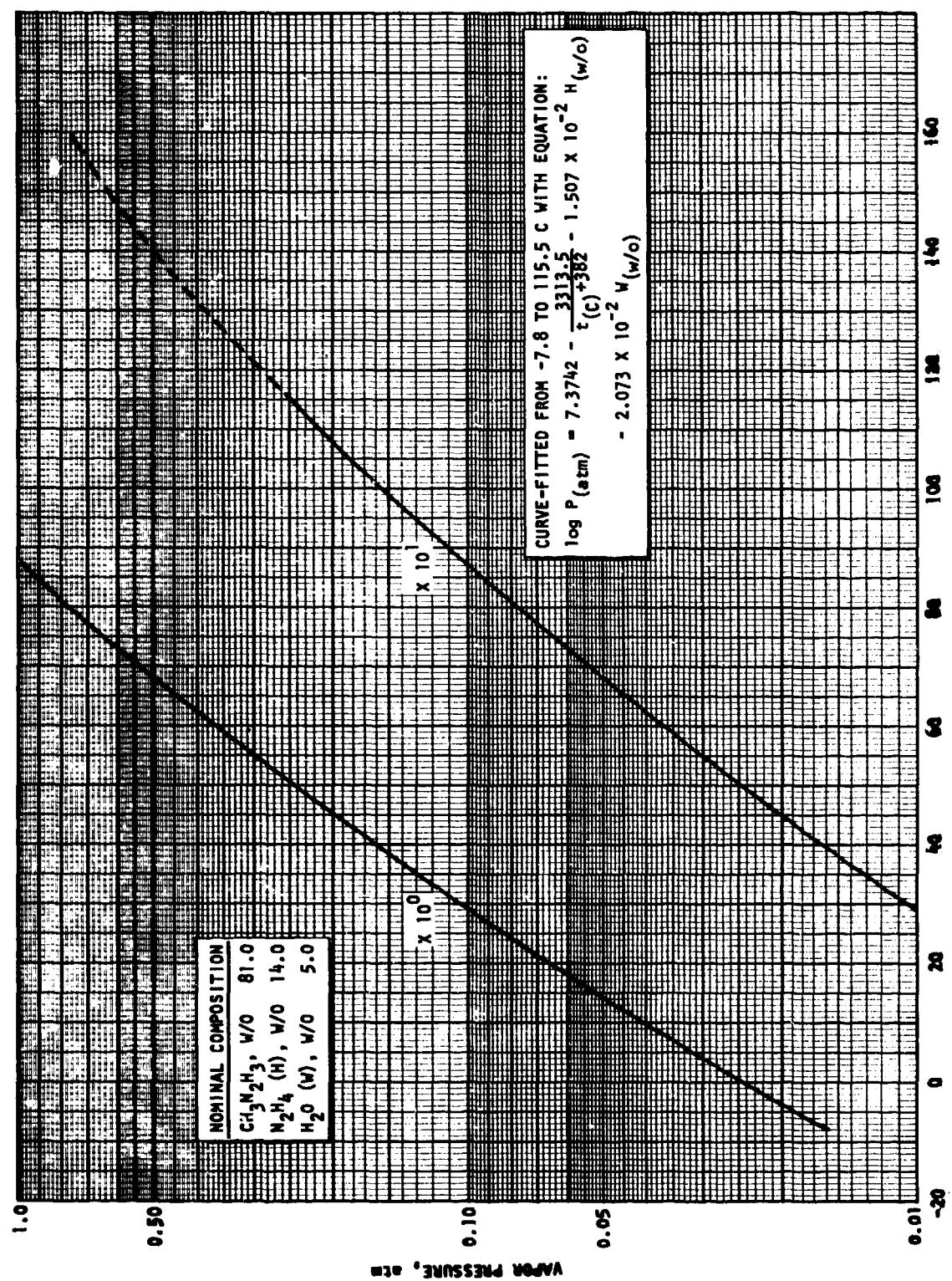


Figure G-3. Vapor Pressure of MHF-7 (Ref. G-2)

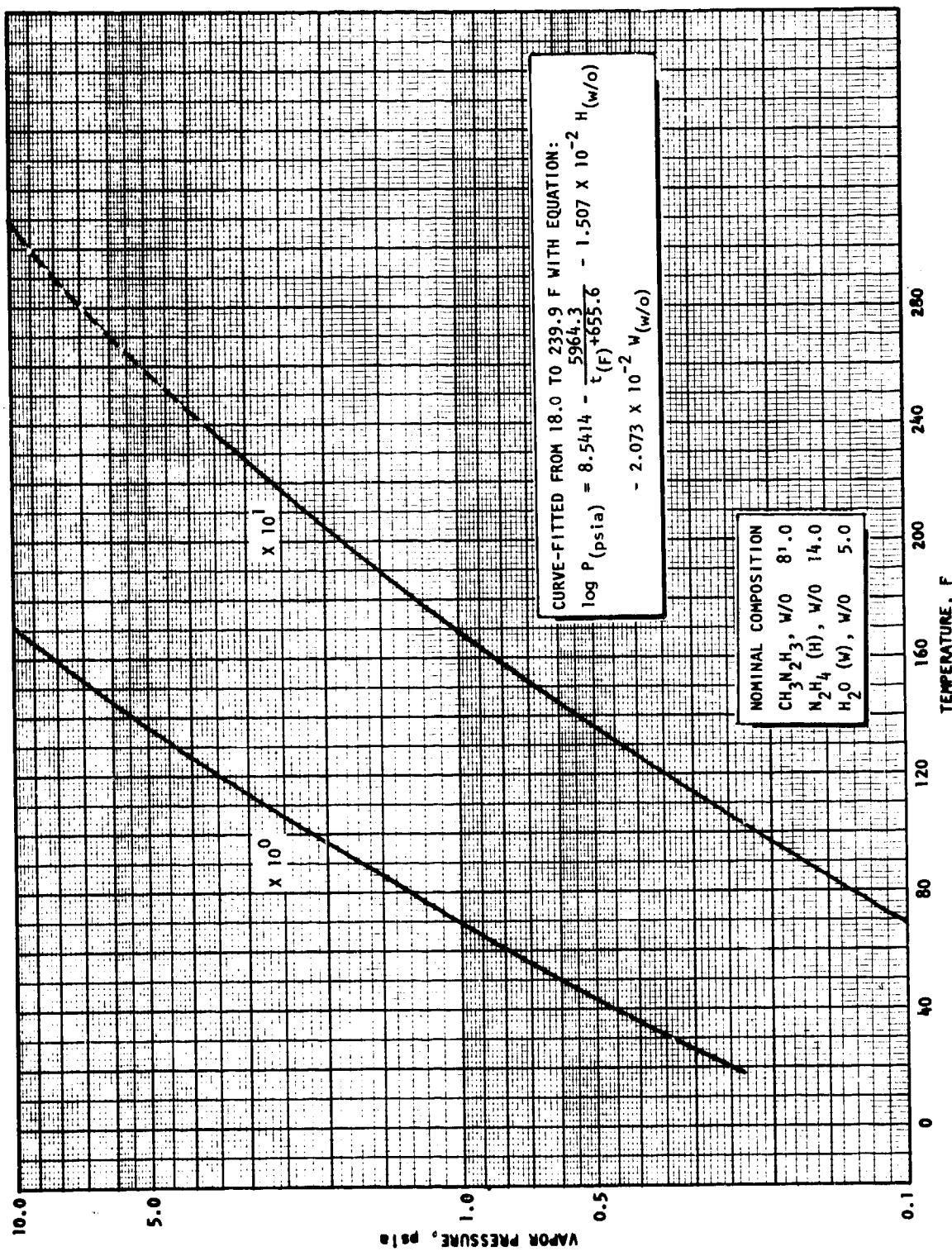


Figure G-3a. Vapor pressure of MHF-7 (Ref. G-2)

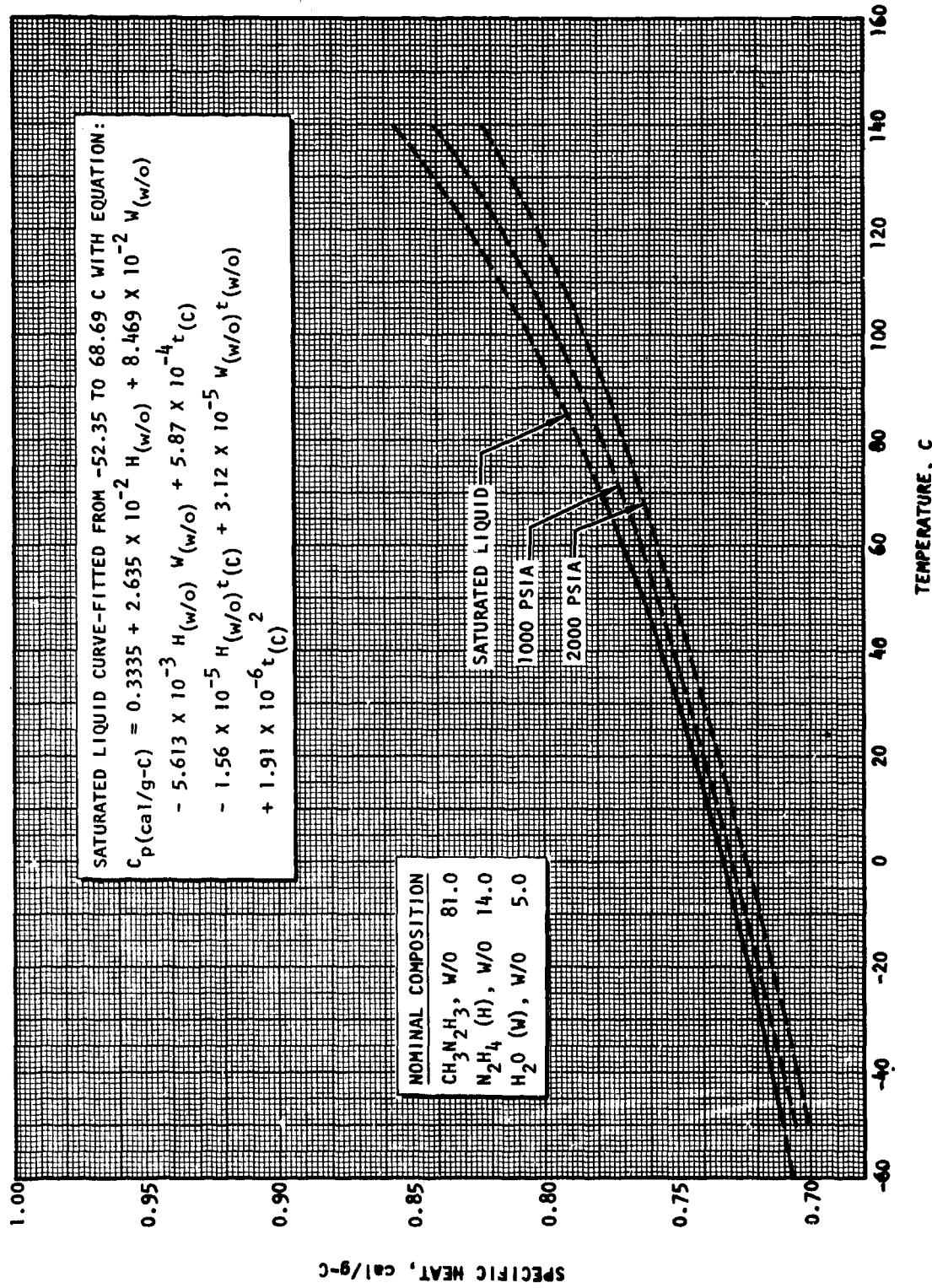


Figure 6-4. Specific Heat of Liquid MHF-7 (Ref. G-2)

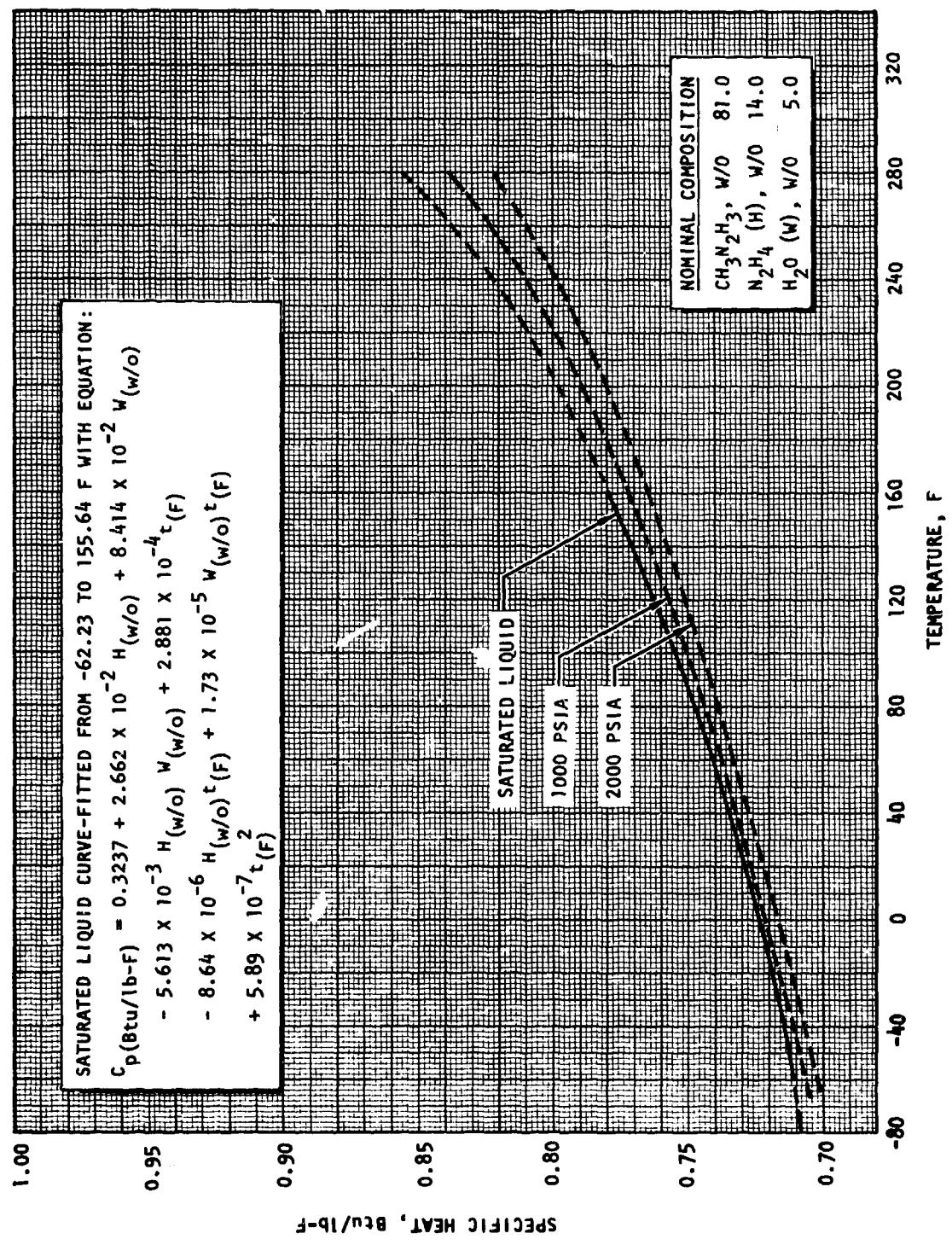


Figure G-4a. Specific Heat of Liquid MHF-7 (Ref. G-2)

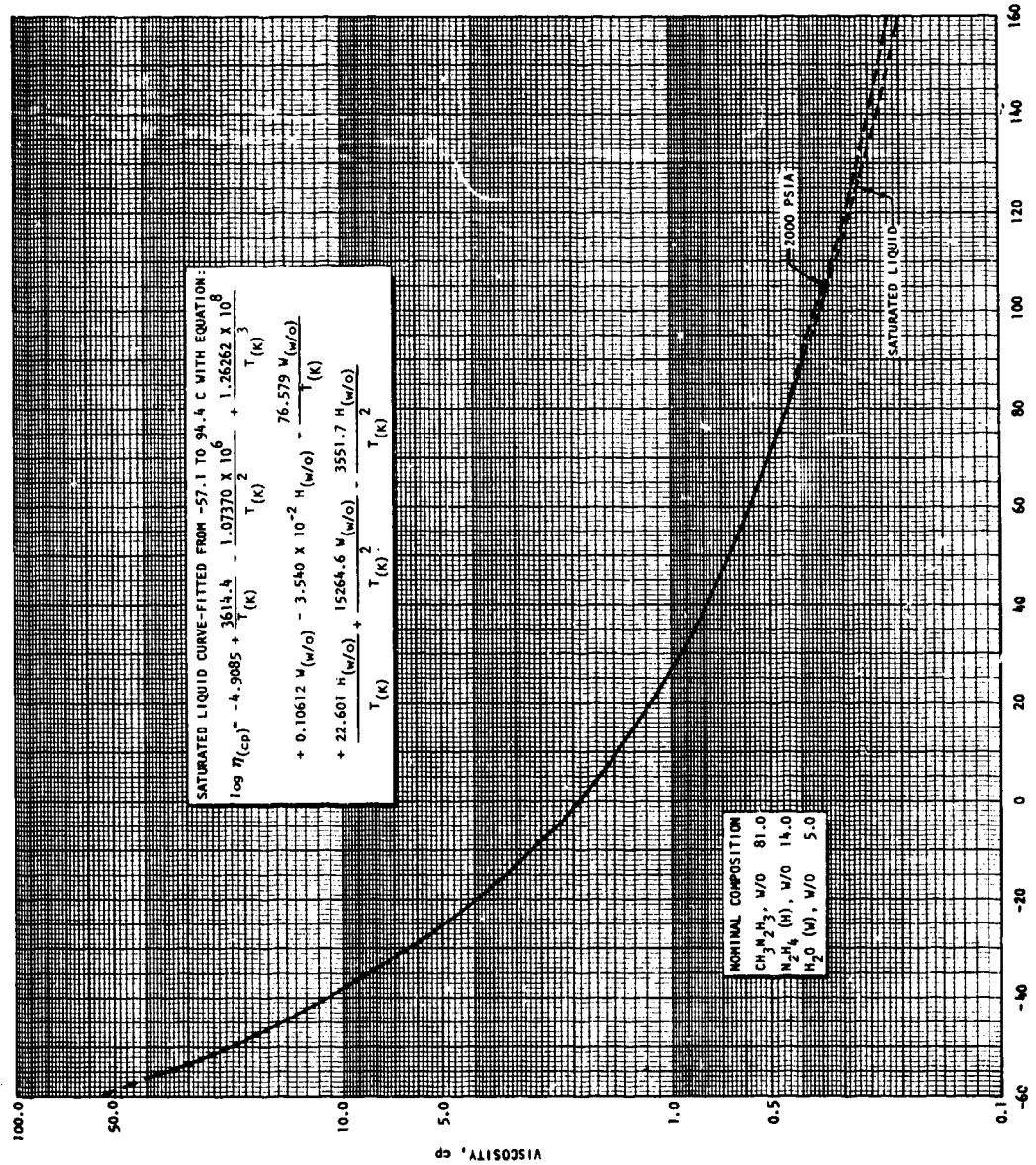


Figure G-5. Viscosity of Liquid MHF-7 (Ref. G-2)

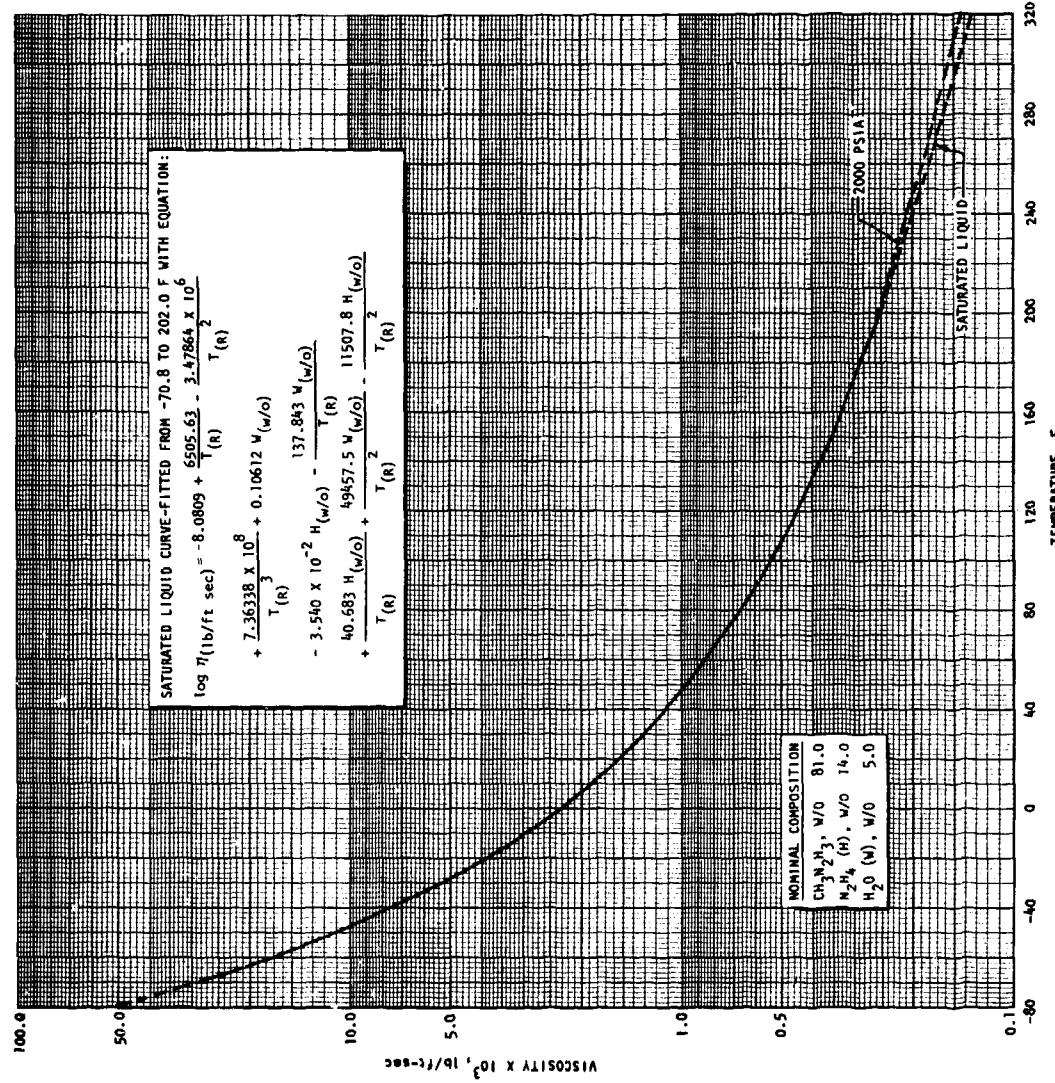


Figure G-5a. Viscosity of Liquid MHF-7 (Ref. G-2)

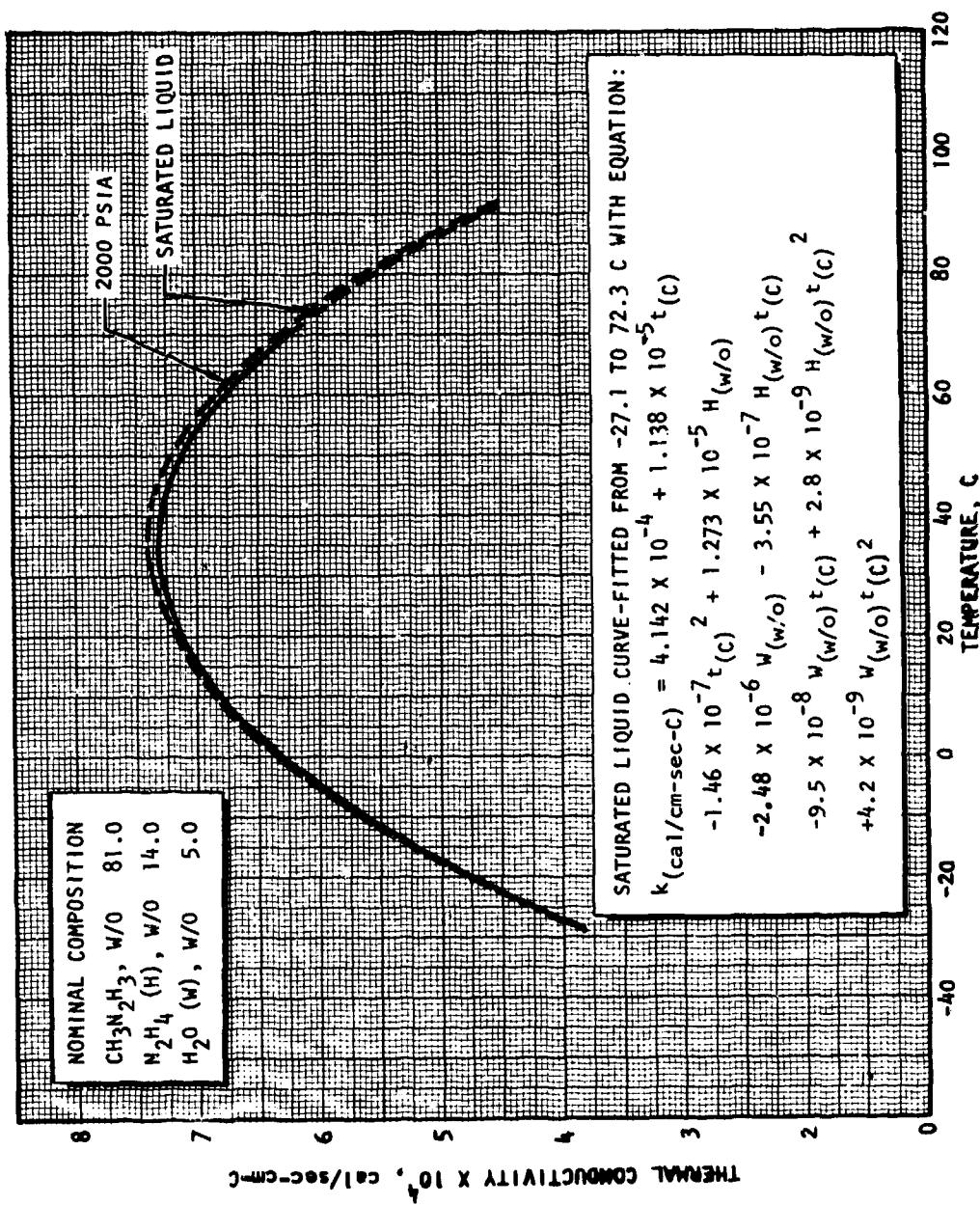


Figure G-6. Thermal Conductivity of Liquid MF-7 (Ref. G-2)

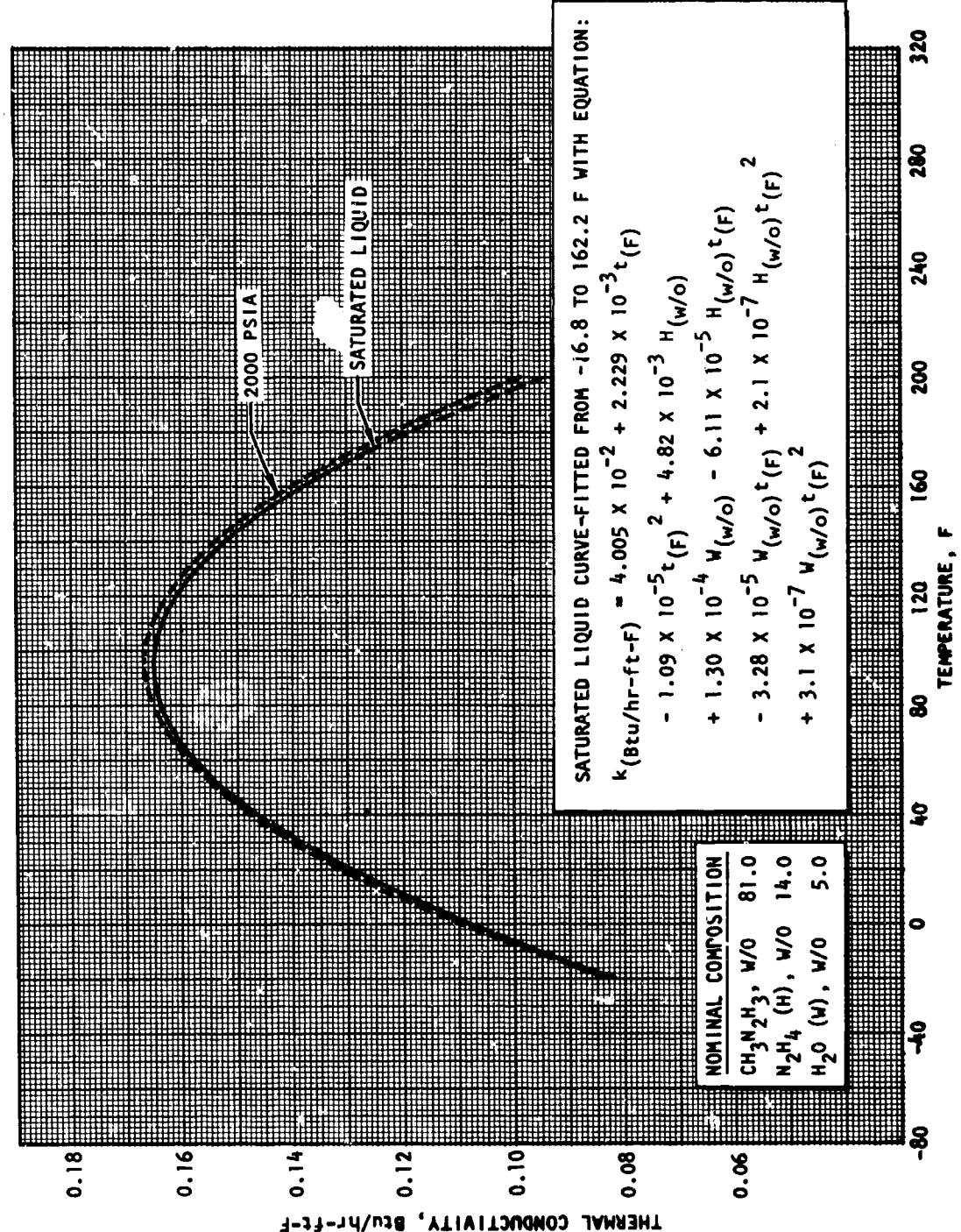


Figure G-6a. Thermal Conductivity of Liquid MHF-7 (Ref. G-2)

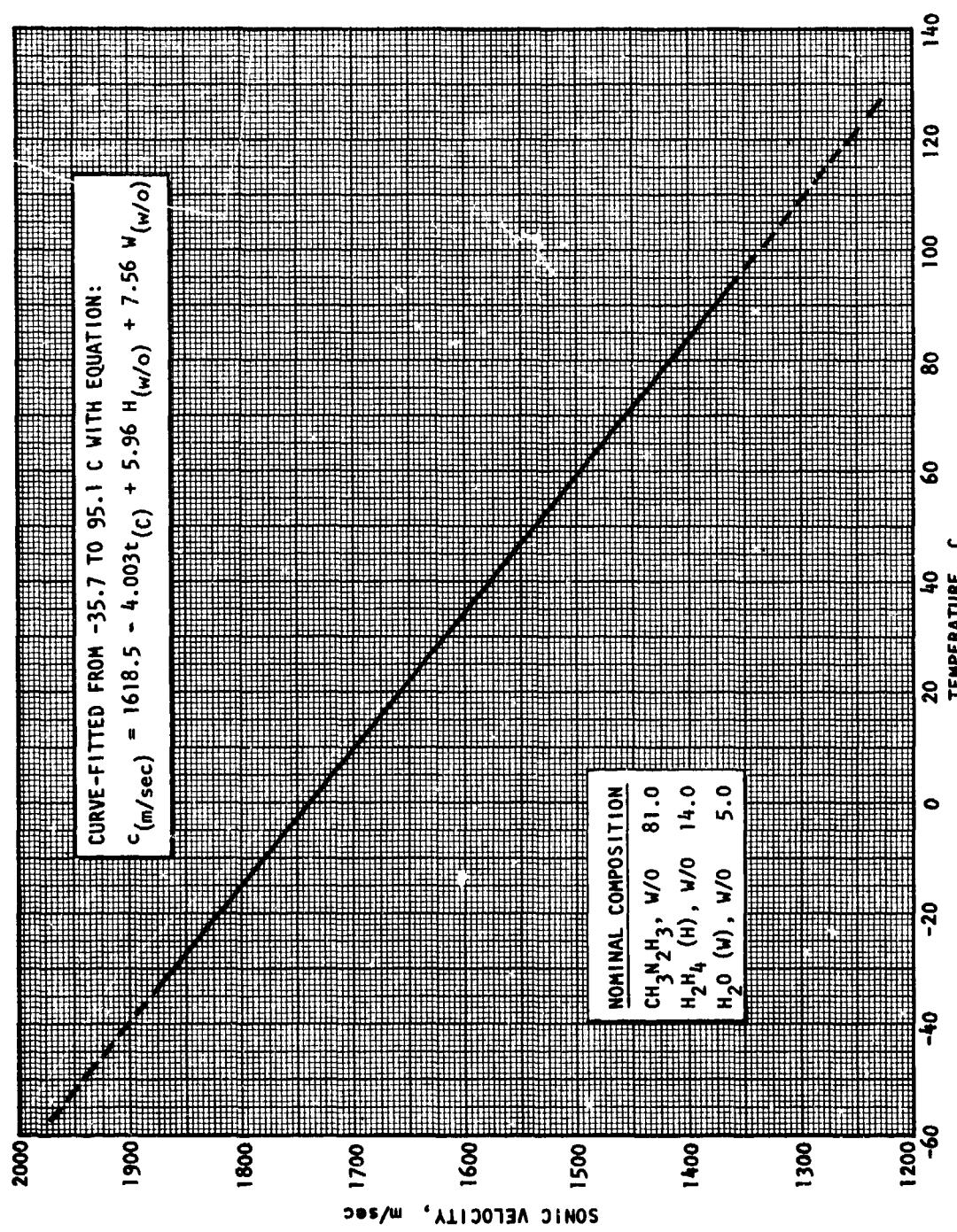


Figure G-7. Velocity of Sound in Saturated Liquid MFH-7 (Ref. G-2)

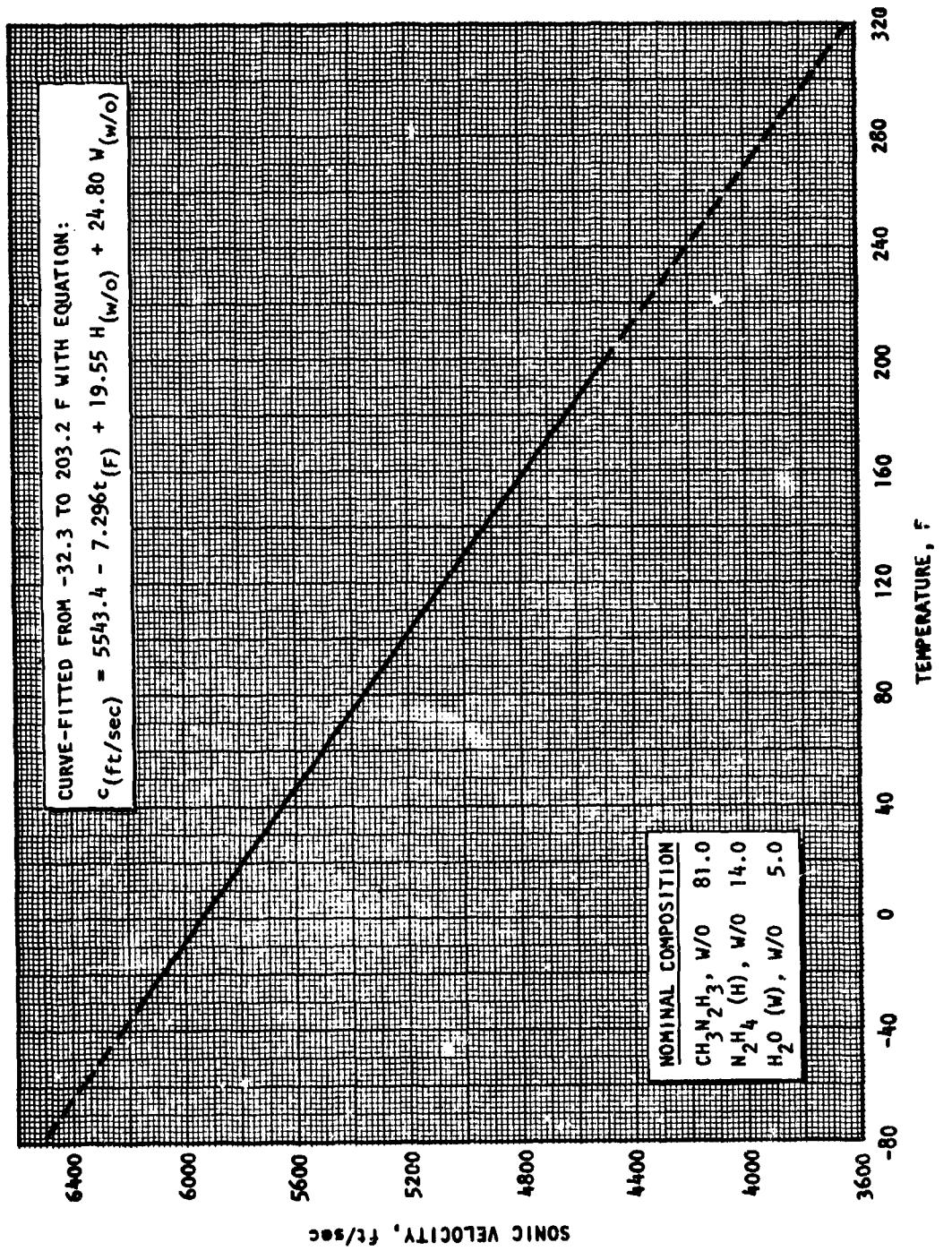


Figure G-7a. Velocity of Sound in Saturated Liquid MHF-7 (Ref. G-2)

APPENDIX H

BIBLIOGRAPHY OF ClF₅/ AND ClF₃/MATERIALS INTERACTION STUDIES

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13. ABSTRACT The results of a 28-month program on the analytical and experimental characterization of the physical properties of selected liquid propellants are presented in three phases. In Phase I, a continual review of the literature was conducted to ensure the acquisition and documentation of current propellant properties data. Phase II experimental efforts have resulted in measurements of: (1) MON-25, Florox, and MHF-7 melting points; (2) IMDFNA, Florox, MOR-5, and MHF-7 densities; (3) IMDFNA vapor and equilibrium pressures, and Florox, MOR-5, and MHF-7 vapor pressures (with calculations of normal boiling points and heats of vaporization of these propellants); (4) N_2O_4 and MON-25 surface tensions; (5) MON-25, Florox, MOR-5, and MHF-7 specific heats; (6) Florox, MOR-5, and MHF-7 viscosities; (7) ClF_5 , ClF_3 , Florox, MOR-5, and MHF-7 thermal conductivities; (8) MON-25, Florox, N_2H_4 , MMH, UDMH, 50% N_2H_4 - 50% UDMH, MHF-3, MHF-5, and MHF-7 sonic velocities (and calculations of their adiabatic compressibilities); and (9) N_2H_4 - $N_2H_5N_3$ and Florox thermal stabilities. In addition, long-term storability tests were initiated on Florox, ClF_5 , ClF_3 , MHF-3, and MHF-5 in selected metals. Phase III efforts resulted in the preparation of physical property data sheets on MMH, C_2N_2 , MON, the fuming nitric acids, Florox, MOR-5, and MHF-7; and the assembly of a bibliography on ClF_5 and ClF_3 /materials interactions. (U)

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Melting Point/Triplet Point Temperature Measurements Normal Boiling Point Density Measurements Vapor and Equilibrium Pressure Measurements Adiabatic Compressibility Surface Tension Measurements Heat of Vaporization Specific Heat Measurements Viscosity Measurements Thermal Conductivity Measurements Sonic Velocity Measurements Thermal Stability Measurements Propellant Storability and Compatibility Propellant Formulation and Chemical Analysis Chlorine Pentafluoride (ClF ₅) Chlorine Pentafluoride Mixtures Chlorine Trifluoride (ClF ₃) Cyanogen (C ₂ N ₂) Florox (ClF ₃ O) Florox Mixtures, MOR-5 Fuming Nitric Acids Hydrazine (N ₂ H ₄) Hydrazine Azide (N ₂ H ₅ N ₃) Hydrazine Mixtures Hydrazine, momomethyl- (CH ₃ N ₂ H ₃) Hydrazine, Monomethyl- Mixtures Hydrazine Nitrate Hydrazine, Unsymmetrical Dimethyl IMDFNA MDFNA MHF-3 MHF-5 MHF-7 Mixed Oxides of Nitrogen MMH MON-10 MON-25 MON-30 Nitrogen Tetroxide Nitrogen Tetroxide Mixtures Propane RFNA UDMH UDMH Mixtures WFNA						

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